## Wisconsin Highway Research Program Proposal

# Wisconsin Mixture Characterization Using the Simple Performance Tests (SPTs) on Historical Aggregate Structures

## Prepared by

Ramon Bonaquist, Ph.D., P.E.
Chief Operating Officer
Advanced Asphalt Technologies, LLC
108 Powers Court, Suite 100
Sterling, Virginia 20166
703-444-4200
aatt@erols.com

March 23, 2007





March 23, 2007

Mr. Andrew Hanz 2258 Engineering Hall 1415 Engineering Drive Madison, WI 53706

RE: Wisconsin Highway Research Program Project, Mixture Characterization Using the Simple Performance Tests (SPTs) on Historical Aggregate Structures

Dear Mr. Hanz:

Advanced Asphalt Technologies, LLC (AAT) is pleased to present this proposal for the subject project. AAT has teamed with the University of Wisconsin-Madison to perform the work described in this proposal. AAT will serve as the prime contractor. Testing with the SPT equipment in the Wisconsin Department of Transportation's Traux Laboratory will performed by a graduate student from the University of Wisconsin-Madison who will be trained by an experienced engineer from AAT.

AAT has been a leader in the performance testing of hot mix asphalt since its inception in 1994. AAT was instrumental in the development of the Simple Performance Test System in NCHRP Projects 9-19 and 9-29. We developed the equipment specifications for the Simple Performance Test System, evaluated and performed ruggedness testing on Simple Performance Test Systems from three manufacturers, and provided training in the use of the Simple Performance Test System to highway agencies, research centers, and contractors. Additionally, AAT has used the simple performance tests on several research and consulting projects.

I will serve as Principal Investigator. Work by the University of Wisconsin-Madison will be under the direction of Dr. Hussain Bahia.

Please contact me if you require any additional information. We look forward to the opportunity to work with the Wisconsin Highway Research Program on this challenging and important project.

Sincerely,

Ramon Bonaquist, Ph.D., P.E.

**Chief Operating Officer** 

### **Table of Contents**

Signature	1
Table of Contents	2
Problem Statement	3
Research Objectives	3
Summary of Proposed Approach	3
Background and Significance of Work	5
Simple Performance Test System	5
Simple Performance Tests and Criteria	5
Summary	8
Benefits	8
Implementation	8
Detailed Work Plan	8
Task 1: Select Mixtures and Assemble Performance Data	8
Task 2: Prepare Test Specimens	9
Task 3: Perform Simple Performance Tests	10
Task 4: Compare Simple Performance Test Properties and Performance	11
Task 5: Compile Final Report	12
Work Time Schedule	12
Reports	12
Qualifications of the Research Team	14
Ramon Bonaquist, Ph.D., P.E Principal Investigator	16
Dr. Hussain Bahia – Co Principal Investigator	17
Donald Jack—Laboratory Manager	17
Robert Bennett – Senior Technician	18
David Tederick – Senior Technician	18
Facilities Available	20
References	24
Appendix A. Draft Simple Performance Test System Standards	25

#### **Problem Statement**

This proposal is submitted in response to the Wisconsin Highway Research Program Fiscal Year 2008 Request for Proposal: *Wisconsin Mixture Characterization Using the Simple Performance Tests (SPT's) on Historical Aggregate Structures.* The proposed project addresses an important step in the implementation of mechanistic approaches for pavement structural design and hotmix asphalt (HMA) mixture design by highway agencies. Both the Mechanistic-Empirical Pavement Design Guide (MEPDG) developed in National Cooperative Highway Research Program (NCHRP) Project 1-37A, and the updated HMA mixture design procedure being assembled in NCHRP Project 9-33 use engineering and performance properties obtained from the simple performance tests. Information on these properties for mixtures that are historically used in Wisconsin will be extremely valuable as the Wisconsin Department of Transportation evaluates and considers the implementation of the new mechanistic pavement and HMA design methods.

#### **Research Objectives**

The objectives of the proposed research are to collect simple performance test properties on mixtures currently used by the Wisconsin Department of Transportation and to compare these properties to the observed performance of pavements built with similar mixtures. The project and the resulting database of simple performance test properties and observed performance will serve several purposes including:

- Provide typical simple performance test properties for mixtures used by the Wisconsin Department of Transportation classified by design traffic level, position in the pavement structure, and aggregate geology.
- Initial comparisons of simple performance test properties and pavement performance for selected Wisconsin projects.
- Local validation of criteria for rutting resistance developed in major national research efforts.
- Input data for evaluation and initial use of the MEPDG.
- Training of Wisconsin Department of Transportation staff in the use of the Simple Performance Test System for pavement and HMA design and evaluation.

#### **Summary of Proposed Approach**

Advanced Asphalt Technologies, LLC's (AAT's) proposed approach to this project is designed to achieve all project objectives, within the specified budget and schedule. The proposed project consists of five tasks:

- Task 1: Select Mixtures and Assemble Performance Data
- Task 2: Prepare Test Specimens
- Task 3: Perform Simple Performance Tests
- Task 4: Compare Simple Performance Test Properties and Performance
- Task 5: Compile Final Report

Task 1 will involve selection of approximately 12 mixtures for characterization using the dynamic modulus and flow number tests from the Simple Performance Test System. The mixtures will be selected considering the design traffic level, position in the pavement structure,

and aggregate type. Task 1 will also include assembling available performance data for the mixtures that are selected.

In Task 2, materials for the mixtures selected in Task 1 will be obtained and simple performance test specimens will be prepared at AAT's laboratory in Sterling, VA for subsequent testing at the Wisconsin Department of Transportation's Traux Laboratory. Task 2 will also include binder testing to obtain binder input data for various dynamic modulus and flow number predictive models.

In Task 3, the dynamic modulus and flow number tests will be conducted using the Simple Performance Test System in the Traux Laboratory by a graduate student from the Asphalt Research Group at the University of Wisconsin-Madison. The graduate student will receive training in the operation of Simple Performance Test System and analysis of the data from an experienced engineer from AAT. Wisconsin Department of Transportation staff will be encouraged to participate in this training.

The simple performance test properties collected in Task 3 and the performance data assembled in Task 1 will be analyzed in Task 4. The major analyses envisioned include:

- Comparison of dynamic modulus and flow number characteristics for various mixtures used by the Wisconsin Department of Transportation.
- Comparison of dynamic modulus and repeated load characteristics with the observed performance of Wisconsin pavements.
- Validation of criteria for rutting resistance developed in NCHRP Project 9-19 for the dynamic modulus test and NCHRP 9-33 for the flow number test.
- Evaluation of available predictive models for dynamic modulus and flow number for Wisconsin mixtures.

The final task, Task 5, consists of compiling a report that thoroughly documents the project. The report will be prepared in accordance with the Wisconsin Highway Research Program requirements. An electronic database of the simple performance test results will be included with the final report.

Dr. Ramon Bonaquist, P.E., will serve as Principal Investigator for the project. Dr. Bonaquist has over 21 years of research and practical experience in asphalt materials and flexible pavement engineering. He has lead the development of the Simple Performance Test System, serving as Principal Investigator on NCHRP Project 9-29, *Simple Performance Tester for Superpave Mixture Design*. Work in AAT's laboratory will be under the direction of Mr. Donald Jack. Mr. Jack is a NICET Level IV Technician with over 20 years experience in asphalt materials testing. He is experienced with performing a wide variety of performance tests on HMA including the simple performance tests. Work by the University of Wisconsin-Madison will be under the direction of Dr. Hussain Bahia. Dr. Bahia has served as the Principal Investigator on several Wisconsin Department of Transportation projects. Dr. Bahia is extremely familiar with the type of mixtures used by the Wisconsin Department of Transportation and the databases that are available.

#### **Background and Significance of Work** Simple Performance Test System

The Simple Performance Test System, shown in Figure 1, was developed in NCHRP Project 9-29 to conduct the three performance related tests that were recommended in NCHRP Project 9-19 to compliment the Superpave volumetric mixture design method. These are flow time, flow number, and dynamic modulus. Data from all three tests were shown to correlate well with observed rutting in field pavements (1). The dynamic modulus is also the primary material input for HMA characterization in the MEPDG developed in NCHRP Project 1-37A. Thus, the Simple Performance Test System can be used to obtain performance related properties of HMA for both mixture design and pavement structural design.



Figure 1. Photograph of the IPC Global Simple Performance Test System.

Substantial development and testing work for the Simple Performance Test System was completed by AAT in NCHRP Project 9-29. This included the development of a detailed equipment specification, the evaluation of three first article devices, ruggedness testing for the dynamic modulus and flow number tests, and the preparation of three draft AASHTO Standards for (1) specimen fabrication, (2) testing, and (3) data analysis (2). There are currently three manufacturers of the Simple Performance Test System: Interlaken Technology Corporation, IPC Global Ltd, and Medical Device Testing Services, Inc. Approximately 25 units have been sold to highway agencies, research centers, and hot-mix asphalt producers in the United States.

#### **Simple Performance Tests and Criteria**

Although the Simple Performance Test System is capable of performing three performance related tests, only the dynamic modulus and flow number tests have been applied in pavement design and HMA mixture analysis. The flow time test was envisioned as an inexpensive alternative to the flow number test; however, interest in the flow time test has faded with the development of the Simple Performance Test System, which cost approximately \$60,000.

#### Dynamic Modulus Test

In the dynamic modulus test, an HMA specimen at a specified temperature is subjected to continuous sinusoidal, stress-controlled loading. Both the applied stress and the resulting strain are recorded with time. The dynamic modulus is defined as the peak stress divided by the peak strain. It is the overall stiffness of the HMA mixture at a particular test temperature and loading frequency.

#### Dynamic Modulus in Pavement Design

In the MEPDG stresses and strains in the pavement are computed using layered elastic theory. The dynamic modulus of the HMA is the material property for use in this analysis. Dynamic moduli for different temperatures and frequencies of loading can be combined using the principle of time-temperature superposition to form a master curve. A typical dynamic modulus master curve obtained from shifting of test data is shown in Figure 2. As part of NCHRP Project 9-29 a practical procedure for developing dynamic modulus master curves for use in structural design

was developed (3). This procedure involves testing replicate specimens at three temperatures and four loading rates. The data are then fit to Equation 1 to determine the master curve parameters. The fitting is easily done using the Solver function within Mircrosoft Excel™. AAT developed a spreadsheet to perform the fitting as part of NCHRP 9-29.

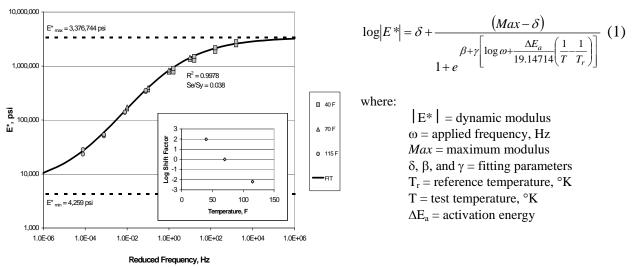


Figure 2. Example Dynamic Modulus Master Curve (3).

#### Dynamic Modulus as a Performance Test

In research conducted in NCHRP Project 9-19, dynamic modulus data at high temperatures correlated well with the rutting resistance of mixtures used in experimental sections at MNRoad, WesTrack, and the FHWA Pavement Testing Facility (1). Figure 3 shows an example of the relationship between rutting and dynamic modulus obtained in NCHRP Project 9-19 for the FHWA Pavement Testing Facility sections. The rutting resistance of the mixtures increased as the dynamic modulus at high temperatures increased.

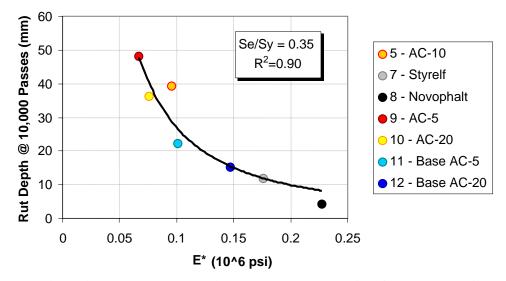


Figure 3. Relationship Between Dynamic Modulus and Rutting for the FHWA Pavement Testing Facility Sections (1).

Recently as part of NCHRP Project 9-19 and NCHRP Project 9-22, researchers at the Arizona State University developed criteria for using the dynamic modulus test to assess rutting resistance (4). The criteria are in the form of a Microsoft Excel™ workbook that interpolates a database of predicted rut depths obtained from many runs of the MEPDG. Users have the flexibility to consider up to three HMA layers and to specify the allowable rut depth in each layer. Other inputs include climatic data, traffic volume, and traffic speed. The workbook returns the conditions for the dynamic modulus test (temperature and frequency), and the critical value of dynamic modulus needed to limit rutting to the specified level.

#### Flow Number Test

In the flow number test, a test specimen, at a specific test temperature, is subjected to a repeated haversine axial compressive load pulse of 0.1 sec every 1.0 sec. The test may be conducted with or without confining pressure. The resulting permanent axial strains are measured as a function of time and numerically differentiated to calculate the flow number. The flow number is defined as the number of load cycles corresponding to the minimum rate of change of permanent strain.

In research conducted in NCHRP Project 9-19, flow number data at high temperatures correlated well with the rutting resistance of mixtures used in experimental sections at MNRoad, WesTrack, and the FHWA Pavement Testing Facility (1). Figure 4 shows an example of the relationship between rutting and flow number obtained in the Project 9-19 research for the FHWA Pavement Testing Facility sections.

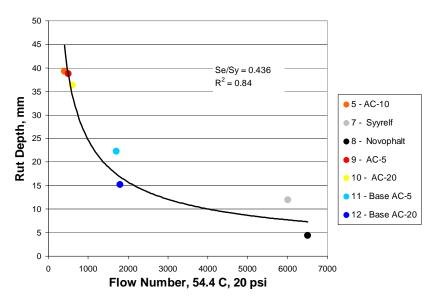


Figure 4. Relationship Between Flow Number and Rutting for the FHWA Pavement Testing Facility Sections (1).

Recently, tentative criteria for the flow number test have been developed in NCHRP Project 9-33. The criteria are shown in Figure 5. These are based on flow number test data collected by the Federal Highway Administration on several field projects and a relationship between mixture volumetric properties and rutting resistance developed in NCHRP Projects 9-25 and 9-31 (5). The criteria shown in Figure 5 are for a rut depth of 10 mm.

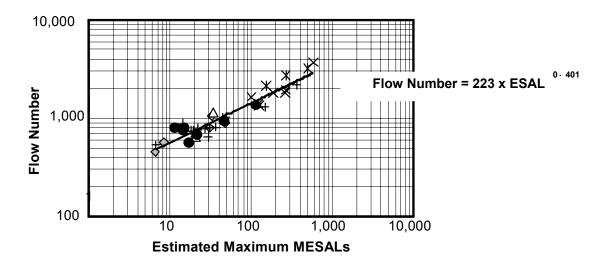


Figure 5. Tentative Criteria for the Flow Number Test (5).

#### **Summary**

Substantial effort has been expended in several NCHRP Projects to develop and implement the simple performance tests. User friendly equipment was developed in NCHRP Project 9-29, and is currently available from three vendors. Dynamic modulus master curves for use with the MEPDG can be generated with the Simple Performance Test System. Criteria for rutting resistance have been developed for the dynamic modulus test and the flow number test.

#### **Benefits**

The proposed research will be extremely valuable to the Wisconsin Department of Transportation as it evaluates and considers the implementation of the new mechanistic pavement and HMA design methods. The findings from this study will provide a link between current practice and likely future practice. This will minimize risks associated with the future implementation of these new technologies. Additionally, the findings may uncover situations where current practice may not be effective or is overly conservative. If these situations occur, adjustments to current mixture design practice based on the findings from this study will result in more efficient pavements with a resulting cost savings to the public.

#### **Implementation**

The findings from this research can be implemented immediately. The performance related mixture properties and analyses developed in this project will either confirm that current practice is acceptable or indicate areas where current practice may be modified in the future. The research findings will assess whether predictive models and performance criteria developed in national research require local calibration for Wisconsin conditions. A plan for implementation activities has been integrated into Tasks 4 and 5 of the detailed work plan.

#### **Detailed Work Plan**

#### Task 1: Select Mixtures and Assemble Performance Data

During Task 1, the research team will meet with representatives from the Wisconsin Department of Transportation to select specific mixtures to be included in the project. Based on the available budget, the number of mixtures included in the project will be limited to 12. This number of mixtures does not permit a factorial experiment to be conducted. Fortunately, the mixture specification used by the Wisconsin Department of Transportation provides logical changes in mixture properties based on design traffic level and position in the pavement structure. Therefore, design traffic level and position in the pavement structure will be the primary variables considered in the selection of mixtures for the study. Variations in aggregate geology will also be included to provide mixtures from the three predominant sources used in Wisconsin: limestone, granite, and gravel. An important factor in the selection of specific mixtures for the project will be the availability of observed pavement performance data for the mixture.

Dr. Hussain Bahia will be responsible for the selection of the specific mixtures to be included in the project. He has served as Principal Investigator on previous projects that included a substantial amount of testing of Wisconsin mixtures. He is very familiar the Wisconsin Department of Transportation specifications for HMA, the materials that are typically used, and the types of performance data available in the Department's databases. Dr. Bahia will be assisted in this task by a graduate student from the Asphalt Research Group at the University of Wisconsin-Madison, who will be responsible for assembling the performance data that will be used in the analyses discussed in Task 4 below.

#### **Task 2: Prepare Test Specimens**

Task 2 includes five subtasks: (1) collection of detailed mixture design data, aggregates, and binder for the mixtures included in the project; (2) shipment of these materials to AAT's laboratory in Sterling, VA; (3) fabrication of simple performance test specimens; (4) binder testing, and (5) shipment of the completed test specimens to the University of Wisconsin-Madison for subsequent testing in the Traux Laboratory. A graduate student from the Asphalt Research Group at the University of Wisconsin will coordinate the collection of detailed mixture design data and materials from Wisconsin sources and shipment to AAT. The proposed testing plan requires 5 test specimens for each mixture; 2 for the dynamic modulus testing, and 3 for the flow number testing. Additionally, two trial specimens and a maximum specific gravity test are needed to adjust the compaction process to reach the target air void content in the test specimens. Each specimen requires approximately 6.5 kg of mix and the maximum specific gravity test requires an additional 2 kg of mix. Thus, a total of approximately 50 kg of each mix will be required. Sufficient materials for 75 kg of each mixture will be shipped to AAT. This will provide extra material in case the sampled material does not match the gradation used in the mixture design, or additional trial specimens are needed to obtain the target air void content.

Test specimen fabrication will be performed by Senior Technicians at AAT under the direction of AAT's Laboratory Manager, Mr. Donald Jack. AAT's laboratory has prepared a large number of simple performance test specimens for several major

research projects including, NCHRP Projects 9-19, 9-25, 9-29, 9-31, 9-34, and 9-36. Specimen fabrication will follow the procedures described in the document, *Proposed Standard Practice for Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor*, that was developed by AAT during NCHRP Project 9-29. A copy of this document and other proposed standards developed by AAT for the Simple Performance Test System are included in Appendix A of this proposal. Each grade of binder included in the experiment will be tested to obtain binder properties for use in predictive models that have been developed for the dynamic modulus and flow number. This will consist of a developing master curves for Rolling Thin Film Oven conditioned samples using the dynamic shear rheometer and the bending beam rheometer.

The completed test specimens will be shipped to the University of Wisconsin-Madison for subsequent testing in the Simple Performance Test System at the Traux Laboratory. Specimen fabrication and shipment will be coordinated with the testing to minimize specimen aging.

#### **Task 3: Perform Simple Performance Tests**

Two simple performance tests will be conducted on each mixture: dynamic modulus and flow number. All of the simple performance tests will be performed at the Traux Laboratory by a graduate student from the Asphalt Research Group at the University of Wisconsin-Madison. This graduate student will receive training in the use of the Simple Performance Test System and associated analysis tools by Dr. Ramon Bonaquist. Dr. Bonaquist has presented similar training to several organizations including the Utah Department of Transportation, the Jiangsu Transportation Research Institute in Nanjing, China, the University of Massachusetts, Dartmouth, and Barrett Paving, an operating unit of Colas, Inc. The staff of the Wisconsin Department of Transportation who may use the Simple Performance Test System will be encouraged to participate in this training. The Simple Performance Test System has been designed to be a user-friendly system, for practicing engineers and technicians.

Dynamic modulus master curves will be developed for each mixture using the procedure described in the document, *Proposed Standard Practice for Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Concrete Using the Simple Performance Test System*, that is included in Appendix A of this proposal. This practice sets the temperatures and rates of loading to be used in the master curve testing and also describes the procedure for fitting the master curve to the measured data. At each temperature and frequency of loading, the testing will be performed as described in the document, *Proposed Standard Test Method for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Simple Performance Test System.* The Simple Performance Test System includes several data quality statistics that indicate the quality of the test data at the time it is collected, allowing the operator to make adjustments and repeat tests as necessary. Part of the Simple Performance Test System training is directed at interpretation of the data quality indicators and changes that should be made to improve the quality of the dynamic modulus test data. Master curves will be developed from the individual dynamic modulus data using the Excel<sup>TM</sup> workbook,

*MasterSolver 2.1*, developed by AAT in NCHRP Project 9-29. Two replicate samples will be used in the dynamic modulus testing.

The flow number test will be conducted on three replicate samples of each mixture; flow number test data are more variable than dynamic modulus test data. The flow number test will be performed as described in the document, *Proposed Standard Test Method for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Simple Performance Test System.* The research team will monitor developments in NCHRP Projects 9-33 and 9-30A and will use appropriate testing conditions based on progress in these projects. The tentative criteria for the flow number test presented in the Background section of this proposal are based on testing at the 7 day average maximum high pavement temperature using an unconfined test a 690 kPa axial stress. NCHRP Project 9-30A is aimed at improving the rutting model used in the MEPDG. The research team for this project is considering the use of a confined flow number test to better characterize rutting resistance. AAT is a member of both of these research teams. Dr. Bonaquist will select testing conditions for the flow number testing based on developments in these projects.

#### Task 4: Compare Simple Performance Test Properties and Performance

In Task 4, various analyses of the simple performance test and pavement performance data will be made. The primary objective of these analyses will be to relate the simple performance test data from mixtures historically used by the Wisconsin Department of Transportation to observed pavement performance. These analyses will be performed jointly by Dr. Bonaquist, Dr. Bahia, and a graduate student from the Asphalt Research Group at the University of Wisconsin-Madison. The types of analyses that are envisioned are discussed below.

#### **Compare Simple Performance Test Properties**

The mixtures in the testing program will include planned variations in design traffic level, aggregate type, and position in the pavement structure. Comparisons of dynamic modulus and flow number data across these major experimental factors will be made. The purpose of these comparisons is to demonstrate how current Wisconsin Department of Transportation mixture specifications influence the performance related properties measured by the Simple Performance Test System.

#### **Compare Simple Performance Test Properties to Observed Performance**

Each mixture included in the test program will have observed performance data obtained from the Wisconsin Department of Transportation Pavement Information Files. The dynamic modulus and flow number data will be compared to the performance data. The purpose of this comparison is to document the level of performance associated with various performance related properties for various design traffic levels.

#### Validate Criteria for Rutting Resistance

As discussed in the Background section of this proposal, criteria for rutting resistance have been developed for the dynamic modulus in NCHRP Project 9-19 and for the flow number in NCHRP Project 9-33. The data collected in this study will be used to validate

these criteria for Wisconsin conditions. For the dynamic modulus criteria, the critical dynamic modulus associated with various allowable rut depths can be compared to the measured dynamic modulus and the observed rutting. For the flow number criteria, the validation will be a pass-fail analysis based on a rut depth of 10 mm and the estimated traffic for the pavement sections included in the study.

#### **Evaluation of Predictive Models**

Various predictive models for the dynamic modulus and flow number have been developed in other national research studies. These models predict the dynamic modulus and flow number from volumetric properties of the mixture and the properties of the binder used in the mixture. These models have the potential to be used in specifications for mixture design and acceptance. The measured dynamic modulus and flow number data from this study will be used to validate these predictive models for Wisconsin mixtures. If the models are found to be reasonably accurate, they may serve as the basis for future specification changes.

#### **Implementation Details**

The results of analysis in Task 4 will be used to develop an implementation plan with the following goals and objectives. The total budget for this implementation plan will be \$15,000 and an extra duration of 3 months based on scheduling of Regional presentations.

#### **Implementation Objectives**

The objectives of the implementation portion of this project:

- Further refine the findings of research project 0092-08-06 so as to put it into a practical technology format with user-friendly terms for use by HMA producers and mix designers.
- Develop and define an effective general implementation practice that will promote use of mechanistic methodologies in differentiating between mixtures.
- Identify and list deliverables necessary for implementation success.
- Evaluate the effectiveness of the implementation effort.

#### **Implementation Goals**

The following goals and tasks summarize the process to meet the primary project objectives related to the implementation portion of the project.

- Identify "what" is to be impacted by the results of the research.
- Provide required work plan documents.
- Outline a marketing strategy to focus on education and sharing of information.
- Create additional RFPs (related topics, enhanced scope for future research, etc)
- Continued documentation validating/tracking user comments and satisfaction.

#### **Task 5: Compile Final Report**

In Task 5, the research team will prepare the Final Report for the project, documenting all significant work completed during the project. The report will be prepared in accordance with the Wisconsin Highway Research Program requirements. A Draft Final Report will be compiled by the research team and submitted to the Technical Oversight Committee

for review and comment. The research team will address the comments, then compile and submit the Final Report. An electronic database of the simple performance test results will be included with the Final Report. Dr. Bonaquist will be responsible for preparing the Final Report with assistance from Dr. Bahia and a graduate student from the Asphalt Research Group at the University of Wisconsin-Madison. Upon near completion of the final report the research team will work to complete the following tasks to meet the implementation objectives and goals.

#### **Task 1)** Technical Document and Concept Presentation Preparation

- a) Prepare technical documents and concept presentation to facilitate knowledge transfer.
- b) Develop best practices list for testing protocol.
- c) Summarize data, conclusions and recommendations of the final report.

#### **Task 2)** Marketing Strategy for Knowledge Transfer

- a) Identify applicable process areas and/or groups within WISDOT (flowchart) for document submittals (impact to user groups)
- b) Provide concept presentation at pertinent conferences and technical meetings as well as scheduling presentations within each Regional office.

#### Task 3) Follow up

- a) Feedback (document live audience comments during presentations, compile Q&A from presentation evaluations)
- b) Measurement of Satisfaction (identify use/users and any benefit realized)
- c) Draft any additional RFPs for future research needs.

#### **Expenditure Breakdown**

Task No.	Percent Effort
Task 1	50%
Task 2	35%
Task 3 Approximately 15% of Total Project cost	15%

#### Expected Deliverables

- SPT Guidance (interpretation/clarification for TP-69)
- Summarized version of the final report (8-10 page executive summary)
- Draft RFP(s)
- Technology Transfer Presentation
- Follow-up documentation and/or audience evaluations of presentation materials

#### **Work Time Schedule**

Figure 6 present the proposed time schedule. This schedule assumes that the contract will begin on October 1, 2007 and have a duration of 12 months. Selection of the materials to be used in the project will be made in the first month of the project. The available performance data will be assembled in the second month of the project. Specimen fabrication and simple performance testing will occur during months 3 through 7 of the project. The on-site training of the graduate student and interested Wisconsin Department of Transportation staff will occur in month 4 of the project. Data analysis will be performed in months 8 and 9. The Draft Final Report will be submitted at the end of the 10 month of the project. One month is provided for the Technical Oversight Committee to review the Draft Final Report. The Revised Final Report will be submitted at the end of 12 month.

Task/Activity	Contract Month														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Task 1: Select Mixtures and Assemble Performance Data	Х	Х													
Task 2: Prepare Test Specimens			Х	Х	Х	Х									
Task 3: Perform Simple Performance Tests				Х	Х	Х	Х								
Task 4: Compare Simple Performance Test Properties and Performance								X	Х						
Implementation Planning												X	X		
Task 5: Compile Final Report									Х	Х		х			
Implementation Activites													X	X	X
Quarterly Reports			Х			Х			Х			Х			
Draft Final Report										Х					
Revised Final Report												X			

Figure 6. Project Schedule.

#### **Reports**

As part of the proposed work, AAT will submit four Quarterly Progress Reports, a Draft Final Report and a Revised Final Report. The Quarterly Progress Reports will be submitted no later than the 7<sup>th</sup> day following the end of in the quarter in the format required by the Wisconsin Highway Research Program. The Final Report will thoroughly document the project and will be prepared in accordance with the requirements of the Wisconsin Highway Research Program.

#### **Qualifications of the Research Team**

The proposed research team includes members of Advanced Asphalt Technologies, LLC, (AAT) and the University of Wisconsin-Madison. A letter of commitment from the University of Wisconsin-Madison is presented at the end of this section. Table 3 is a summary of the proposed project personnel and their responsibilities.

The proposed team has extensive experience in the technical areas critical to the successful completion of the project including: asphalt mixture design, asphalt mixture performance testing, the Simple Performance Test System, pavement performance analysis, asphalt binder rheology, pavement design and construction, and technology transfer. Members of the research team have played key roles in many related research projects including:

- NCHRP 1-37A, Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures: Phase II
- NCHRP 9-19, Superpave Support and Performance Models Management
- NCHRP 9-25, Requirements for Voids in Mineral Aggregate for Superpave Mixtures
- NCHRP 9-29, Simple Performance Tester for Superpave Mixture Design
- NCHRP 9-30A, Calibration of Rutting Models for HMA Structural and Mix Design
- NCHRP 9-31, Air Void Requirements for Superpave Mix Design
- NCHRP 9-33, A Mix Design Manual for Hot Mix Asphalt
- Wisconsin DOT Project, Guidelines for PG Binder Selection for Wisconsin
- Wisconsin DOT Project, Using the Gyratory Compactor to Measure Mechanical Stability of Asphalt Mixtures
- Wisconsin DOT Project, Evaluation of Superpave Mixes Designed with Different PG Grades and Aggregate Angularity

The research team will be supported by AAT's laboratory that specializes in asphalt materials testing. Work not performed in the Wisconsin Department of Transportation's Traux Laboratory will be performed in AAT's AMRL accredited laboratory that was developed specifically to provide engineering and testing services for asphalt concrete mixtures and asphalt binders. A copy of AAT's current laboratory accreditation is included in the next section of this proposal.

The sections that follow present summaries of relevant experience for each of the named staff in Table 3.

Table 3. Key Research Team Members.

Name/Role	Project Role	Address and Phone
Dr. Ramon Bonaquist, P.E. Principal Investigator	<ul> <li>Overall project management and reporting.</li> <li>Point of contact with Wisconsin Department of Transportation.</li> <li>Simple Performance Test System training.</li> <li>Analyze and interpret laboratory data and pavement performance.</li> <li>Compile quarterly project reports</li> <li>Compile final project report</li> </ul>	Advanced Asphalt Technologies, LLC 108 Powers Court, #100 Sterling, VA 20166 (703) 444-4200
Dr. Hussain Bahia Co-Principal Investigator	<ul> <li>Mixture selection.</li> <li>Manage University of Wisconsin-Madison activities.</li> <li>Analyze and interpret laboratory data and pavement performance.</li> <li>Compile final project report</li> </ul>	University of Wisconsin-Madison Civil and Environmental Engineering 3350 Engineering Hall 1415 Engineering Drive Madison, WI 53706-1691 (608) 265-4481
Mr. Donald Jack Laboratory Manager	<ul> <li>Overall responsibility for specimen fabrication and binder testing.</li> <li>Supervise other laboratory technicians involved in project.</li> <li>Prepare Simple Performance Test specimens.</li> </ul>	Advanced Asphalt Technologies, LLC 108 Powers Court, #100 Sterling, VA 20166 (703) 444-4200
Mr. Robert Bennett Senior Technician	<ul> <li>Prepare Simple Performance Test specimens</li> <li>Binder testing.</li> </ul>	Advanced Asphalt Technologies, LLC 108 Powers Court, #100 Sterling, VA 20166 (703) 444-4200
Mr. David Tederick Senior Technician	<ul> <li>Prepare Simple Performance Test specimens</li> <li>Binder testing.</li> </ul>	Advanced Asphalt Technologies, LLC 108 Powers Court, #100 Sterling, VA 20166 (703) 444-4200
Graduate Student	<ul> <li>Assemble pavement performance data.</li> <li>Collect mix design information and materials.</li> <li>Ship materials to AAT.</li> <li>Perform Simple Performance Tests and compile data.</li> <li>Assist with data analysis</li> <li>Assist with compiling Final Report</li> </ul>	University of Wisconsin-Madison Civil and Environmental Engineering 2205 Engineering Hall 1415 Engineering Drive Madison, WI 53706-1691 (608) 262-3542

#### Ramon Bonaquist, Ph.D., P.E.- Principal Investigator

Dr. Bonaquist will serve as Principal Investigator. He will be directly responsible for all technical and administrative aspects of the project. He will serve as task leader for all project tasks. He will assign specific work to other team members, and perform all necessary reporting. Dr. Bonaquist will be responsible for data analysis and the preparation of the final report. He will also provide training in the use of the Simple Performance Test System to the University of Wisconsin-Madison graduate student and the Wisconsin Department of Transportation staff.

Dr. Bonaquist has over 21 years of research and practical experience in asphalt materials and flexible pavement engineering. He has been AAT's Chief Operating Officer since 1997, developing AAT into one of the country's leading asphalt materials consulting firms. In this capacity he serves as Chief Engineer and also leads AAT's strategic business planning and development. Since joining AAT he served as Principal Investigator, Co-Principal Investigator, or Program Manager on several large projects including NCHRP Project 9-29, Simple Performance Tester for Superpave Mix Design, NCHRP 9-36, Improved Procedure for Laboratory Aging of Asphalt Binders in Pavements, and NCHRP 9-30A, Calibration of Rutting Models for HMA Structural and Mix Design.

Prior to joining AAT, Dr. Bonaquist held two research management positions at the Federal Highway Administrations' Turner-Fairbank Highway Research Center. From 1995 to 1997 he led the FHWA Asphalt Materials Research Team, a multi-disciplinary team consisting of 10 professionals and 5 technicians with an annual research budget of \$5 million. He was responsible for work conducted in three FHWA laboratories: the Bituminous Mixtures Laboratory, the Pavement Binders Laboratory, and the Pavement Testing Facility. From 1987 to 1995, Dr. Bonaquist was Manager of the Pavement Testing Facility, FHWA's full-scale accelerated pavement testing laboratory. Research he directed at the Pavement Testing Facility is well respected in the international pavements community and earned him four FHWA technical accomplishment awards. From 1985 to 1987, Dr. Bonaquist was a materials engineer with Law Engineering Testing Company. He was responsible for a number of pavement design, pavement construction, materials testing and forensic investigation projects.

Dr. Bonaquist is the Chair of Transportation Research Board Committee AFK50 *Characteristics of Bituminous Materials to Meet Structural Requirements*, and Co-Chair of the FHWA Asphalt Mixture and Construction Expert Task Group. He has been a member the Association of Asphalt Paving Technologists (AAPT) since 1985 and is currently serving as a Director at Large. He is also a member of the American Society of Civil Engineers and a member of the editorial board for the *International Journal of Pavement Engineering*. Dr. Bonaquist was co-recipient of AAPT's W.J. Emmons Award for best paper in 2002.

Dr. Bonaquist received B.S. and M.S. degrees in Civil Engineering from The Pennsylvania State University in 1982 and 1985, respectively. He received his doctorate in Civil Engineering from the University of Maryland in 1996. Dr. Bonaquist is a registered Professional Engineer in Virginia and Maryland.

#### Dr. Hussain Bahia - Co Principal Investigator

Dr. Bahia will serve as Co-Principal Investigator managing the efforts of the Asphalt Research Group at the University of Wisconsin-Madison. He is will be responsible for selection of the mixtures to be used in the project and will assist with data analysis and reporting. Dr. Bahia is currently participating in two projects related to the implementation of the MEPDG in Wisconsin. He has served as Principal Investigator on four projects in which significant testing of Wisconsin mixtures was conducted. He is very familiar with the Wisconsin Department of Transportation HMA specifications, the types of mixtures used, and the databases available at the Department.

Dr. Bahia received his Ph.D. degree in the area of Pavement Materials and Design from the Pennsylvania State University in 1991. He joined the faculty at the University of Wisconsin-Madison in 1996 to teach and conduct research in the area of pavement materials and design. Prior to joining the University of Wisconsin faculty, he served as the Director of Research and Engineering Services of the Asphalt Institute in 1995- 1996. He also served for four years after earning his Ph.D. on the faculty of Penn State University from 1991 to 1994.

He has served as the Principal Investigator, or as the co-Principal Investigator, on several Wisconsin DOT projects (more than 10 major studies), projects with FHWA (4 major studies), and numerous projects funded by private Industry (more than 20 studies). He served as the Principal Investigator of NCHRP 9-10 project from 1996 to 2000 and also served as a member of the NCHRP project panels for project 9-19 and project 9-23.

Dr. Bahia has authored or co-authored more than 80 peer reviewed technical publications in the area of paving materials and pavement performance. He has also co-authored a large number of technical reports to various public and private agencies. He has served as a consultant to many companies and agencies in the United States, South America, the Middle East, and South Africa. He is one of the associate editors of the International Journal on Road Materials and Pavement Design.

He serves as a member of three TRB committees, has served as a member of the asphalt binder ETG for many years, and is a member of ASCE, AAPT, ISAP, and RILEM. Currently he serves as the chair of the RILEM Task Group 2 on HMA Compaction and Design and is an associate editor of the International Journal of Road Materials and Pavement Design. He is a Professor of Highway Materials at the University of Wisconsin and is the coordinator of the Asphalt Research Group at the University of Wisconsin

#### **Donald Jack—Laboratory Manager**

Mr. Donald Jack will oversee all laboratory work at AAT. Mr. Jack has been AAT's Laboratory Manager the last four years.

Mr. Donald Jack has over 20 years of experience in asphalt mixture design and laboratory testing of asphalt materials from a variety of sources including the Federal Highway Administration, the Asphalt Institute, the Pennsylvania Transportation Institute, and Advanced Asphalt Technologies. He currently holds a Level 4 certification from the National Institute for Certification in Engineering Technologies (NICET) in asphalt and is a Certified Superpave

Technician in Virginia. Both of these are the highest level of certification available from the respective agency.

Mr. Jack has performed mixture designs for a number of research and private consulting projects. He is also experienced conducting a wide range of asphalt mixture performance tests including the simple performance tests. Mr. Jack has also been an instructor for the laboratory portion of PennDOT's asphalt technician certification courses conducted by the Northeast Center of Excellence for Pavement Technology.

#### Robert Bennett - Senior Technician

Mr. Robert Bennett will serve as Senior Technician. He has over 16 years of experience in asphalt materials with AAT and its predecessor, Novophalt America, first as a Blending Technician and Project Manager, then as a Senior Technician. Mr. Bennett is a Certified PG Asphalt Binder Laboratory Technician through the New England Transportation Technician Certification Program.

#### **David Tederick - Senior Technician**

Mr. David Tederick will serve as Senior Technician. He has over 12 years of experience in asphalt materials with AAT and its predecessor, Novophalt America, first as a Blending Technician, then as a Technician and Senior Technician. Mr. Tederick has an Asphalt Plant Certification from the Virginia Department of Transportation and a Superpave Level I certification from the Maryland State Highway Administration.



2210 Engineering Building 1415 Johnson Drive Madison, Wisconsin 53706 Telephone: (608) 265-4481 FAX: (608) 262-5199 e-Mail bahia@engr.wisc.edu

3/23/07

Dr. Ramon Bonaquist, PhD, PE Principal Investigator Advanced Asphalt Technologies, LLC 108 Powers Court, #100 Sterling, VA 20166

Dear Ray,

RE: WisDOT Research Project "Wisconsin Mixture Characterization Using the SPT on Historical Aggregate Structures

This letter is to inform you that I will be happy to join your team to conduct the research proposed for the Wisconsin DOT Project mentioned above.

My groups' role will include providing support for laboratory testing and preparation of samples to be tested at the DOT laboratories in Madison, Wisconsin. In addition we will assist in collecting information regarding the various mixture variables and historical information about WI HMA. I will also be happy to participate in writing reports as you see required. Our fees will be as described in the budget details that we have jointly prepared.

I look forward to this opportunity to work with you and your team. If you have any questions, please feel free to contact me.

Best Regards,

Hussain U. Bahia, Ph.D.

Hussain U. Bahin

Professor of Civil and Environmental Engineering

#### **Facilities Available**

Testing with the Simple Performance Test Equipment will be performed at the Wisconsin Department of Transportation's Traux Laboratory by a graduate student from the Asphalt Research Group at the University of Wisconsin-Madison. Fabrication of the simple performance test specimens and binder master curve testing will be performed in AAT's laboratory in Sterling, VA.

AAT's AASHTO accredited, state of the art materials testing laboratory occupies approximately 10,000 square feet. This laboratory is fully equipped to conduct a range of research and specification testing of asphalt binders, aggregates, and asphalt concrete mixtures.

AAT's laboratory is currently accredited by AASHTO for the following tests.

Asphalt Binders	AASHTO/ASTM
Bending Beam Rheometer	T313/D6648
Dynamic Shear Rheometer	T315
Direct Tension	T314/D6723
Pressure Aging Vessel	R28/D6521
Rotational Viscosity	T316/D4402
Elastic Recovery	T301/D6084
Force Ductility	T300
Flash Point	T48/D92
Ductility	T51/D113
Softening Point	T53/D36
Specific Gravity	T228/D70
Rolling Thin Film Oven Test	T240/D2872
Hot Mix Asphalt Concrete	
Gyratory Compaction	T312/D6925
Percent Air Voids	T269/D3203
Mechanical Analysis of Extracted Aggregate	T30/D5444
Quantitative Extraction	T164/D2172
Bulk Specific Gravity of SSD Mix	T166/D2726
Abson Recovery	T170/D1856
Maximum Theoretical Specific Gravity	T209/D2041
Bulk Specific Gravity of Paraffin Coated Specimens	T275
Moisture Sensitivity	T283/D4867
Ignition Oven	T308/D6307
Hot Mix Asphalt Concrete Aggregates	
Washed Sieve Analysis	T11/C117
Specific Gravity and Absorption of Fine Aggregate	T84/C128
Specific Gravity and Absorption of Coarse Aggregate	T85/C127
Reducing Field Samples	T248/C702
Moisture Content	C566
Sieve Analysis of Fine and Coarse Aggregate	T27/C136
	==,, 5155

Sand Equivalent T176/D2419
Uncompacted Void Content of Fine Aggregate T304/C1252
Flat and Elongated Particles D4791
Fractured Particles in Coarse Aggregate D5821

Through its research support activities, AAT has gained experience performing a number of other standard and non-standard tests. The following is an inventory of major equipment now installed in the laboratory:

 Cannon Instruments bending beam rheometer conforming to AASHTO Standard Method of Test T313, Method for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer.



 Bohlin direct tension test device meeting the requirements of AASHTO Standard Method of Test T314, Method for Determining the Fracture Properties of Asphalt Binder in Direct Tension.



• Rheometrics Model RDA II Dynamic Analyzer (research-grade dynamic shear rheometer) exceeding the requirements of AASHTO Standard Method of Test T315, Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer.



• Interlaken gyratory compactor conforming to the requirements of AASHTO T312 Standard Method of Test for Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor.



• Interlaken closed-loop, servo-hydraulic loading system for the dynamic testing of laboratory specimens and pavement cores in creep, compression and tension with and without confinement. This equipment is capable of performing the Project 9-19 simple performance tests, AASHTO Provisional Standard Method of Test TP62, *Dynamic Modulus of Hot Mix Asphalt Concrete Mixtures*, and uniaxial continuum damage fatigue testing.



• Interlaken closed-loop, servo-hydraulic indirect tensile test device conforming to the requirements of AASHTO Standard Method of Test TP322 Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device.



• Interlaken closed-loop, servo-hydraulic biaxial shear test device conforming to the requirements of AASHTO Standard Method of Test T320, Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST).



This compliment of equipment provides for full Superpave performance grading of asphalt binders, and Superpave volumetric mixture design. It also provides the capability to perform a variety of dynamic and static tests for evaluation of the mechanical properties of paving mixes including uniaxial complex modulus, uniaxial creep compliance, uniaxial repeated-load permanent deformation, diametral resilient modulus, indirect tensile creep and strength, biaxial shear tests, and uniaxial direct tension fatigue.

Login



#### AASHTO Materials Reference Laboratory

AASHTO Accreditation Laboratory Assessment Proficiency Testing

#### AASHTO Accreditation Details\*

#### Advanced Asphalt Technologies, LLC

Sterling, Virginia Show This Entry Only Donald P. Jack 108 Powers Court Suite 100 Sterling, VA 20166-9321

Phone: (703) 444-4200 Fax: (703) 444-4368 aatt@erols.com

http://www.advancedasphalt.com

Asphalt Cement / Cutback Asphalt - accredited since 2/15/1996 R28 T48 T51 T53 T228 T240 T300 T301 T313 T314 T315 T316 - D36 D70 D92 D113 D2872 D3666 D4402 D6084 D6521 D6648 D6723 E329

Hot Mix Asphalt - accredited since 2/15/1996 T30 T164 T166 T170 T209 T269 T275 T283 T308 T312 - D1856 D2041 D2172 D2726 D3203 D3666 D4867 D5444 D6307 D6925 E329

Aggregate - accredited since 2/15/1996 T11 T27 T84 T85 T176 T248 T304 - C117 C127 C128 C136 C566 C702 C1252 D2419 D3666 D4791 D5821 E329

\*This information is only valid as of 3/24/2007. Please visit http://www.amri.net for current accreditation status.

Go

Get Documents Here:

#### Notice

Printouts may be outdated Paper copies of this page may be outdated and/or altered. Current accreditation information (test methods, suspensions, and contact details) are poly be suspensions, and contact details) can only be found on the AMRL website. These changes aim to increase the accuracy of the accreditation status for each participating laboratory.

Please Note The dates displayed beside the field of accreditation correspond to the year of initial accreditation in that field.

http://www.amrl.net/Portal/DesktopDefault.aspx?tabindex=99&tabid=49&LaboratoryID=f... 3/24/2007

#### References

- 1. Witczak, M.W., Kaloush, K., Pellinen, T., El-Basyouny, M., and Von Quintus, H., *Simple Performance Test for Superpave Mix Design*, NCHRP Report 465, National Cooperative Highway Research Program, Washington, D.C., 2002.
- 2. Bonaquist, R.F., Chirstensen, D.W., and Stump, W. *Simple Performance Tester for Superpave Mix Design: First Article Development and Evaluation*, NCHRP Report 513, National Cooperative Highway Research Program, Washington, D.C., 2003.
- 3. Bonaquist, R., and Christensen, D.W., "Practical Procedure for Developing Dynamic Modulus Master Curves for Pavement Structural Design, Transportation Research Record 1929, Transportation Research Board, Washington, D.C., 2005.
- 4. Witczak, M.W., "Development of Probabilistic Based PRS Specifications for HMA Using the ME-PDG Distress Models," Presentation to TRB Committee AFK50, January 24, 2007.
- 5. Advanced Asphalt Technologies, LLC, "Quarterly Progress Report For Project NCHRP 9-33: A Mix Design Manual For Hot Mix Asphalt, Submitted to the National Cooperative Highway Research Program, February, 2007.

## **Appendix A. Draft Simple Performance Test System Standards**

#### **Proposed Standard Practice for**

## Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor

**AASHTO Designation: PP XX-XX** 

#### 1. SCOPE

- 1.1 This practice covers the use of a Superpave gyratory compactor to prepare 100 mm diameter by 150 mm tall cylindrical test specimens for use in a variety of axial compression and tension performance tests. This practice in intended for dense, gap-, and open-graded hot mix asphalt concrete mixtures with nominal maximum aggregate sizes to 37.5 mm.
- 1.2 This standard may involve hazardous materials, operations, and equipment, This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to its use.

#### 2. REFERENCED DOCUMENTS

#### 2.1 *AASHTO Standards*

- T 312, Preparation and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor.
- R 30, Mixture Conditioning of Hot-Mix Asphalt (HMA)
- T 166, Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens.
- T 209, Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures.
- T 269, Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures.

#### 2.1.1 *ASTM Standards*

 D 3549, Thickness or Height of Compacted Bituminous Paving Mixture Specimens.

#### 3. TERMINOLOGY

- 3.1 *Gyratory Specimen* Nominal 150 mm diameter by 170 mm high cylindrical specimen prepared in a Gyratory compactor meeting the requirements of AASHTO T 312.
- 3.2 *Test Specimen* Nominal 100 mm diameter by 150 mm high cylindrical specimen that is sawed and cored from the gyratory specimen.
- 3.3 End Perpendicularity The degree to which an end surface departs from being perpendicular to the axis of the cylindrical test specimen. This is measured using a combination square with the blade touching the cylinder parallel to its axis, and the head touching the highest point on the end of the cylinder. The distance between the head of the square and the lowest point on the end of the cylinder is measured with feeler gauges.
- 3.4 End Planeness Maximum departure of the specimen end from a plane. This is measured using a straight edge and feeler gauges.

#### 4. SUMMARY OF PRACTICE

4.1 This practice presents methods for preparing 100 mm diameter by 150 mm tall cylindrical test specimens for use in a variety of axial compression and tension performance tests.

#### 5. SIGNIFICANCE AND USE

- 5.1 This practice should be used to prepare specimens for the following standard tests:
  - Dynamic modulus, AASHTO TP 62-02
  - Flow number, AASHTO TP XX-XX
  - Flow time, AASHTO TP XX-XX
  - Continuum damage fatigue, AASHTO TP XX-XX
- This practice may also be used to prepare specimens for other non-standard tests requiring 100 mm diameter by 150 mm tall cylindrical test specimens.

#### **6.** APPARATUS

6.1 Superpave Gyratory Compactor - A compactor meeting the requirements of AASHTO T 312 and capable of preparing finished 150 mm diameter specimens that a minimum of 170 mm tall.

- **Note 1 -** Research completed to date has not determined if it is critical that the compactor maintain the internal angle specified in AASHTO T 312 when compacting 170 mm tall specimens. Until additional work is completed compactors meeting either the external or internal angle requirements of AASHTO T 312 may be used.
- 6.2 *Mixture Preparation Equipment* Balances, ovens, thermometers, mixer, pans, and other miscellaneous equipment needed to prepare gyratory specimens in accordance with AASHTO T 312 and make specific gravity measurements in accordance with AASHTO T 166, T 209, and T 269.
- 6.3 Core Drill An air or water cooled diamond bit core drill capable of cutting nominal 100 mm diameter cores meeting the dimensional requirements of Section 9.5.3. The core drill shall be equipped with a fixture for holding 150 mm diameter gyratory specimens.
  - Note 2 Core drills with fixed and adjustable rotational speed have been successfully used to prepare specimens meeting the dimensional tolerances given in Section 9.5.3.

    Rotational speeds from 450 750 RPM have been used.
  - **Note 3** Core drills with automatic and manual feed rate control have been successfully used to prepare specimens meeting the dimensional tolerances given in Section 9.5.3.
- 6.4 *Masonry Saw* An air or water cooled diamond bladed masonry saw capable of cutting specimens to a nominal length of 150 mm and meeting the tolerances for end perpendicularity and end flatness given in Section 9.5.3.
  - **Note 4** Single and double bladed saws have been successfully used to prepare specimens meeting the dimensional tolerances given in Section 9.5.3. Both types of saws require a fixture to securely hold the specimen during sawing, and control of the feed rate.
  - **Note 5** In National Cooperative Highway Research Project 9-29, a machine that performs both the sawing and coring operation within the tolerances specified in Section 9.5.3 was developed. Contact: Shedworks, Inc., 2151 Harvey Mitchell Parkway, S., Suite 320, College Station, TX 77840-5244, Phone (979) 695-8416, Fax 695-9629, email <a href="www@shedworks.com">www@shedworks.com</a>
- 6.5 Square Combination square with a 300 mm blade and 100 mm head.
- 6.6 Feeler Gauges Tapered leaf feeler gauges in 0.05 mm increments.
- 6.7 *Metal Ruler* Metal ruler capable of measuring nominal 150 mm long specimens to the nearest 1 mm.

6.8 *Calipers* – Calipers capable of measuring nominal 100 mm diameter specimens to the nearest 0.1 mm.

#### 7. HAZARDS

7.1 This practice and associated standards involve handling of hot asphalt binder, aggregates and asphalt mixtures, and the use of sawing and coring machinery. Use standard safety precautions, equipment, and clothing when handling hot materials and operating machinery.

#### 8. STANDARDIZATION

8.1 Items associated with this practice that require calibration are included in the AASHTO Standards referenced in Section 2. Refer to the pertinent section of the referenced standards for information concerning calibration.

#### 9. PROCEDURE

- 9.1 *HMA Mixture Preparation*
- 9.1.1 Prepare HMA mixture for each test specimen and a companion maximum specific gravity test in accordance with Section 8 of AASHTO T 312.
- 9.1.2 The mass of mixture needed for each specimen will depend on the gyratory specimen height, the specific gravity of the aggregate, the nominal maximum aggregate size and gradation (coarse or fine), and the target air void content for the test specimens. Appendix A describes a trial and error procedure developed in NCHRP Project 9-19 for determining the mass of mixture required to reach a specified test specimen target air void content for gyratory specimens prepared to a height of 170 mm.
  - **Note 6** Test specimens with acceptable properties have been prepared from gyratory specimens ranging in height from 165 to 175 mm. The height of the gyratory specimen that should be used depends on the air void gradient produced by the specific compactor, and the capabilities of the sawing equipment.
- 9.1.3 Perform mixture conditioning for the test specimens and companion maximum specific gravity test in accordance with Section 7.2 of AASHTO R-30, *Short-Term Conditioning for Mixture Mechanical Property Testing*.
- 9.2 *Gyratory Specimen Compaction*
- 9.2.1 Compact the gyratory specimens in accordance with Section 9 of AASHTO T 312.

- 9.2.2 Compact the gyratory specimens to the target gyratory specimen height.
  - Note 7 Each laboratory should determine a target gyratory specimen height based on the procedure for evaluating test specimen uniformity given in Appendix B, and an evaluation of the ability of the sawing equipment to maintain the dimensional tolerances given in Section 9.5.3.
- 9.3 Long-Term Conditioning (Optional)
- 9.3.1 If it is desired to simulate long-term aging, condition the gyratory specimen in accordance with Sections 7.3.4 through 7.3.6 of AASHTO R-30.
- 9.3.2 To obtain accurate volumetric measurements on the long-term conditioned specimens, also condition a companion sample of short-term conditioned loose mix meeting the sample size requirements of AASHTO T 209 in accordance with Sections 7.3.4 through 7.3.6 of AASHTO R-30.
- 9.4 *Gyratory Specimen Density and Air Voids (Optional)*
- 9.4.1 Determine the maximum specific gravity of the mixture in accordance with AASHTO T 209 (If long-term conditioning has been used, determine the maximum specific gravity on the long-term conditioned loose mix sample). Record the maximum specific gravity of the mixture.
- 9.4.2 For dense- and gap-graded mixtures, determine the bulk specific gravity of the gyratory specimen in accordance with AASHTO T 166. Record the bulk specific gravity of the gyratory specimen.
- 9.4.3 For open-graded mixtures, determine the bulk specific gravity of the gyratory specimen in accordance with Section 6.2 of AASHTO T 269.
- 9.4.4 Compute the air void content of the gyratory specimen in accordance with AASHTO T 269. Record the air void content of the gyratory specimen.
  - **Note 8** Section 9.4 is optional because acceptance of the test specimen for mechanical property testing is based on the air void content of the test specimen, not the gyratory specimen. However, monitoring gyratory specimen density can identify improperly prepared specimens early in the specimen fabrication process. Information on gyratory specimen air voids and test specimens air voids will also assist the laboratory in establishing potentially more precise methods than Appendix A for preparing test specimens to a target air void content.
- 9.5 *Test Specimen Preparation*
- 9.5.1 Drill a nominal 100 mm diameter core from the center of the gyratory specimen.

  Both the gyratory specimen and the drill shall be adequately supported to ensure that

- the resulting core is cylindrical with sides that are smooth, parallel, and meet the tolerances on specimen diameter given in Section 9.5.3.
- 9.5.2 Saw the ends of the core to obtain a nominal 150 mm tall test specimen. Both the core and the saw shall be adequately supported to ensure that the resulting test specimen meets the tolerances given in Section 9.5.3 for height, end flatness and end perpendicularity.
  - **Note 9** With most equipment, it is better to perform the coring before the sawing. However, these operations may be done in either order as long as the dimensional tolerances in Section 9.5.3 are met.
- 9.5.3 Test specimens shall meet the dimensional tolerances given in Table 1.

**Table 1. Test Specimen Dimensional Tolerances.** 

Item	Specification	Method
Average Diameter	100 mm to 104 mm	9.5.3.1
Standard Deviation of Diameter	0.5 mm	9.5.3.1
Height	147.5 mm to 152.5 mm	9.5.3.2
End Flatness	0.5 mm	9.5.3.3
End Perpendicularity	1.0 mm	9.5.3.4

- 9.5.3.1 Using calipers, measure the diameter at the center and third points of the test specimen along axes that are 90 ° apart. Record each of the six measurements to the nearest 0.1 mm. Calculate the average and the standard deviation of the six measurements. The standard deviation shall be less than 0.5 mm. Reject specimens not meeting the average and standard deviation requirements listed in Table 1. The average diameter, reported to the nearest 0.1 mm, shall be used in all material property calculations.
- 9.5.3.2 Measure the height of the test specimen in accordance with Section 6.1.2 of ASTM D 3549. Reject specimens with an average height outside the height tolerance listed in Table 1. Record the average height.
- 9.5.3.3 Using a straightedge and feeler gauges, measure the flatness of each end. Place a straight edge across the diameter at three locations approximately 120 ° apart and measure the maximum departure of the specimen end from the straight edge using tapered end feeler gauges. For each end record the maximum departure along the three locations as the end flatness. Reject specimens with end flatness exceeding 0.5 mm.
- 9.5.3.4 Using a combination square and feeler gauges, measure the perpendicularity of each end. At two locations approximately 90 ° apart, place the blade of the combination square in contact with the specimen along the axis of the cylinder, and the head in contact with the highest point on the end of the cylinder. Measure the distance

between the head of the square and the lowest point on the end of the cylinder using tapered end feeler gauges. For each end, record the maximum measurement from the two locations as the end perpendicularity. Reject specimens with end perpendicularity exceeding 1.0 mm.

- 9.6 Test Specimen Density and Air Voids
- 9.6.1 Determine the maximum specific gravity of the mixture in accordance with AASHTO T 209 (If long-term conditioning has been used, determine the maximum specific gravity on the long-term conditioned loose mix sample). Record the maximum specific gravity of the mixture.
- 9.6.2 For dense- and gap-graded mixtures, determine the bulk specific gravity of the test specimen in accordance with AASHTO T 166. Record the bulk specific gravity of the test specimen.
  - Note 10 When wet coring and sawing methods are used, measure the immersed mass followed by the surface dry mass followed by the dry mass to minimize drying time and expedite the specimen fabrication process.
- 9.6.3 For open-graded mixtures, determine the bulk specific gravity of the test specimen in accordance with Section 6.2 of AASHTO T 269. Record the bulk specific gravity of the test specimen.
- 9.6.4 Compute the air void content of the test specimen in accordance with AASHTO T 269. Record the air void content of the test specimen. Reject test specimens exceeding the air void tolerances specified in the appropriate Standard Method of Test.
- 9.7 *Test Specimen Storage*
- 9.7.1 Mark the test specimen with a unique identification number.
- 9.7.2 Unless the test specimen will be tested immediately or be subjected to additional conditioning prior to testing, wrap the test specimen in plastic (Saran Wrap® brand or equivalent). Store the wrapped test specimen on end on a flat shelf in a room with temperature controlled between 15 and 27 °C.
- 9.7.3 To minimize aging effects, store test specimens no more than two weeks before testing.
  - Note 11 Definitive research concerning the effects of test specimen aging on various mechanical property tests has not been completed. The recommendations above provide general guidance based on testing programs that have been completed. The user may wish to exercise more stringent or lenient control on specimen storage.

#### 10. REPORTING 10.1 Unique test specimen identification number. 10.2 Mixture design number for link to pertinent mixture design data including design compaction level and air void content, asphalt binder type and grade, binder content, binder specific gravity, aggregate types and bulk specific gravitities, consensus aggregate properties, and maximum specific gravity. 10.3 Type of aging used. 10.4 Maximum specific gravity for the aged condition. 10.5 Gyratory specimen target height (Optional). 10.6 Gyratory specimen bulk specific gravity (Optional). 10.7 Gyratory specimen air void content (Optional). 10.8 Test specimen average height. 10.9 Test specimen average diameter. 10.10 Test specimen bulk specific gravity. 10.11 Test specimen air void content. 10.12 Test specimen end flatness for each end. 10.13 Test specimen end parallelism for each end. 10.14 Remarks concerning deviations from this standard practice.

#### 11. KEYWORDS

Performance test specimens; gyratory compaction

## APPENDIX A METHOD FOR ACHIEVING TARGET AIR VOID CONTENT (NONMANDATORY INFORMATION)

#### A1. PURPOSE

- A1.1 This Appendix presents a procedure for estimating the mass of mixture required to produce test specimens at a target air void content. It was developed to reduce the number of trial specimens needed obtain a target air void content for a specific mixture.
- A1.2 This procedure can be used with either plant produced or laboratory prepared mixture.

#### A2. SUMMARY

- A2.1 Trial test specimens are prepared as described in this standard practice from gyratory specimens produced with a standard mass of 6,650 g and compacted to a standard height of 170 mm.
- A2.2 Based on the air void content of the trial specimens, the mass of mixture required to produce test specimens at a target air void content is estimated using a regression equation. Background information regarding the regression equation is presented in Section A4.
- A2.3 To use this method, it is critical that all gyratory specimens are prepared to a standard height of 170 mm. The approach described in Section A4 can be used to develop a similar equation for other gyratory specimen heights.

#### A3. PROCEDURE

- A3.1 Prepare trial test specimen 1 and trial test specimen 2 following this standard practice from gyratory specimens produced with a standard mass of 6,650 g and compacted to a standard height of 170 mm.
- A3.2 Determine the air void content of trial test specimen 1 and trial test specimen 2.
- A3.3 Calculate the average air void content of the two specimens and designate this as  $Va_s$ .
- A3.4 Estimate the mass of mixture,  $W_t$ , required to produce test specimens with a target air void content of  $Va_t$  using Equation A1.

 $W_{t} = 7175 - (525) \frac{Va_{t}}{Va_{s}} \tag{A1}$ 

where:

 $W_t$  = estimated mass of mixture required to produce a gyratory specimen for a test specimen with a target air void content of  $Va_t$ , g

 $Va_t$  = target air void content for the test specimen, vol %

 $Va_s$  = test specimen air void content produced with a gyratory mass of 6,650 g, vol %

- A3.5 Prepare trial test specimen 3 following this standard practice from a gyratory specimen produced with the target mass estimated in Section A3.4 and compacted to the standard height of 170 mm.
- A3.6 Determine the air void content of trial test specimen 3.
- A3.7 If the air void content of trial test specimen 3 is within  $\pm$  0.5 percent of the target, use the mass determined in A3.4 as the target mass for test specimen production.
- A3.8 If the air void content of trial test specimen 3 is not within  $\pm$  0.5 percent of the target, prepare trial specimen 4 using 50g less than calculated in A3.4 and trial test specimen 5 using 50g more than calculated in A3.4.
- A3.9 Determine the air void content of trial test specimen 4 and trial test specimen 5.
- A3.10 Plot the air void content of trial test specimens 3, 4, and 5 (y) against the mass of mixture used to prepare the gyratory specimen (x), and draw the best-fit line through the three data points.
- A3.11 From the best-fit line, determine the mass of mixture needed to produce a test specimen with the target air void content.
- A3.12 Use the mass determined in A3.11 as the target mass for test specimen production.

#### A4. BACKGROUND

- A4.1 The method described in this Appendix was developed by the Arizona State University during NCHRP Project 9-19. It is based on analysis of 38 different mixtures, where test specimens were prepared to varying target air void contents representative of in-situ conditions.
- A4.2 For a given mixture, when gyratory specimens are prepared to a specific height, the relationship between the mixture mass used to prepare the gyratory specimen and the air void content of the test specimens was found to be linear.

$$Va = I + S(W) \tag{A2}$$

where:

Va = test specimen air void content, vol %

W =mass of mixture used to produce the gyratory specimen

I =intercept of the regression line

S = slope of the regression line

A4.3 When a wide range of mixtures is considered, the intercepts and slopes for individual mixtures were also found to be linearly related.

$$I = -C(S) \tag{A3}$$

where:

I =intercept of individual mixture regression lines

S = slope of individual mixture regression lines

C = constant

A4.4 In the NCHRP Project 9-19 research, the constant, *C*, was found to be 7,175 for gyratory specimens prepared to a standard height of 170 mm. Substituting this constant into Equation A3, then substituting Equation A3 into Equation A2 and simplifying, yields an equation relating the air void content of the test specimen to the mass of mixture used to prepare the gyratory specimen to the standard height of 170 mm.

$$Va = S(W - 7175) \tag{A4}$$

A4.5 If gyratory specimens are compacted using a standard mass, W<sub>s</sub>, and the air void contents for the resulting test specimens are determined to be Va<sub>s</sub>, then Equation A4 can be solved for the slope.

$$S = \frac{Va_s}{W_s - 7175} \tag{A5}$$

where:

 $Va_s$  = test specimen air void content produced with a gyratory mass of  $W_s$ , vol %

 $W_s$  = mass of mixture used to produce the gyratory specimen, g

S = slope of the regression line

A4.6 Using the slope from Equation A5, the target gyratory specimen mass,  $W_t$ , required to produce a test specimen with a specific air void content,  $Va_t$ , can be estimated by substituting Equation A5 into Equation A4 and simplifying.

$$W_{t} = 7175 + \frac{Va_{t}}{Va_{s}} (W_{s} - 7175) \tag{A6}$$

where:

 $W_t$  = estimated mass of mixture required to produce a gyratory specimen for a test specimen with a target air void content of  $Va_t$ , g

 $Va_t$  = target air void content for the test specimen.

 $Va_s$  = test specimen air void content produced with a gyratory mass of  $W_s$ , vol %

 $W_s$  = mass of mixture used to produce the gyratory specimen

A4.7 For a standard mixture mass of 6,650 g, which was the average mass used in the NCHRP 9-19 study, Equation A6 reduces to.

$$W_{t} = 7175 - (525) \frac{Va_{t}}{Va_{s}} \tag{A6}$$

where:

 $W_t$  = estimated mass of mixture required to produce a gyratory specimen for a test specimen with a target air void content of  $Va_t$ , g

 $Va_t$  = target air void content for the test specimen.

 $Va_s$  = test specimen air void content produced with a gyratory mass of  $W_s$ , vol %

 $W_s$  = mass of mixture used to produce the gyratory specimen

### APPENDIX B TEST SPECIMEN UNIFORMITY (NONMANDATORY INFORMATION)

#### **B1.** PURPOSE

- B1.1 This Appendix presents a procedure for assessing the uniformity of the air void content in test specimens produced using this standard practice.
- B1.2 The approach tests the significance of the difference in mean bulk specific gravity between the top and bottom third of the specimen relative the middle third.
- B1.3 The procedure can be used to determine the height for preparing gyratory specimens with a specific compactor to minimize within sample variations in air voids.

#### **B2.** SUMMARY

- B2.1 Three test specimens are prepared as described in this standard practice from gyratory specimens produced with the same mixture mass and compacted to the same height.
- B2.2 The test specimens are cut into three slices of equal thickness and the bulk specific gravity or each slice is determined.
- B2.3 A statistical hypothesis test is conducted to determine the significance of differences in the mean bulk specific gravity of the top and bottom slices relative to the middle.

#### **B3.** PROCEDURE

- B3.1 Prepare three test specimens following this standard practice to a target air void content of 5.5 percent. All three specimens shall have air void contents within the range of 5.0 to 6.0 percent.
- B3.2 Label the top, middle, and bottom third of each specimen, then saw the specimens at the third points.
- B3.3 Determine the bulk specific gravity of each of the nine test section slices in accordance with AASHTO T 166 for dense- and gap-graded mixtures or AASHTO T 269 for open-graded mixtures.
- B3.4 Assemble a summary table of the bulk specific gravity data where each column contains data for a specific slice, and each row contains the data from a specific core.

B3.5 For each column, compute the mean and variance of the bulk specific gravity measurements using Equations B1 and B2.

$$\overline{y} = \frac{\sum_{i=1}^{3} y_i}{3} \tag{B1}$$

$$s^{2} = \frac{\sum_{i=1}^{3} (y_{i} - \overline{y})^{2}}{2}$$
 (B2)

where:

 $\overline{y}$  = slice mean

 $s^2$  = slice variance

 $y_i$  = measured bulk specific gravities

- B3.6 Statistical Comparison of Means- Compare the mean bulk specific gravity of the top and bottom slices to the middle slice using the hypothesis tests described below. In the descriptions below, subscripts "t", "m", and "b" refer to the top, middle, and bottom slices, respectively.
- B3.6.1 Check the top relative to the middle.

#### **Null Hypothesis:**

The mean bulk specific gravity of the top slice equals the mean bulk specific gravity of the middle slice,  $\mu_t^2 = \mu_m^2$ 

#### **Alternative Hypothesis:**

The mean bulk specific gravity of the top slice is not equal the mean bulk specific gravity of the middle slice,  $\mu_t^2 \neq \mu_m^2$ 

**Test Statistic:** 

$$t = \frac{\left(\overline{y}_t - \overline{y}_m\right)}{0.8165(s)} \tag{B3}$$

where:

$$s = \sqrt{\frac{{s_t}^2 + {s_m}^2}{2}} \tag{B4}$$

 $\overline{y}_t$  = computed mean for the top slices

 $\overline{y}_m$  = computed mean for the middle slices  $s_t^2$  = computed variance for the top slices  $s_m^2$  = computed variance for the middle slices

#### **Region of Rejection:**

For the sample sizes specified, the absolute value of the test statistic must be less than 2.78 to conclude that bulk specific gravity of the top and middle slices are equal.

#### B3.6.2 Check the bottom relative to the middle.

#### **Null Hypothesis:**

The mean bulk specific gravity of the bottom slice equals the mean bulk specific gravity of the middle slice,  $\mu_h^2 = \mu_m^2$ 

#### **Alternative Hypothesis:**

The mean bulk specific gravity of the bottom slice is not equal the mean bulk specific gravity of the middle slice,  $\mu_b^2 \neq \mu_m^2$ 

#### **Test Statistic:**

$$t = \frac{\left(\overline{y}_b - \overline{y}_m\right)}{0.8165(s)} \tag{B5}$$

where:

$$s = \sqrt{\frac{{s_b}^2 + {s_m}^2}{2}} \tag{B4}$$

 $\overline{y}_h =$ computed mean for the bottom slices

 $\overline{y}_m$  = computed mean for the middle slices

 $s_b^2$  = computed variance for the bottom slices  $s_m^2$  = computed variance for the middle slices

#### **Region of Rejection:**

For the sample sizes specified, the absolute value of the test statistic must be less than 2.78 to conclude that bulk specific gravity of the bottom and middle slices are equal.

#### B4. **ANALYSIS**

B4.1 Significant differences in the bulk specific gravity of the top and bottom slices relative to the middle indicate a systematic variation in density within the specimen.

- B4.2 Specimens with differences for the top and/or bottom slices relative to the middle slices on the order of 0.025 have performed satisfactorily in the dynamic modulus, flow number, flow time, and continuum damage fatigue tests.
- B4.3 Changing the height of the gyratory specimen can improve the uniformity of the density in the test specimen.

#### **Proposed Standard Test Method for**

## Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Simple Performance Test System

**AASHTO Designation: PP XX-XX** 

#### 1. SCOPE

- 1.1 The standard describes test methods for measuring the dynamic modulus and flow number for hot-mix asphalt mixtures using the Simple Performance Test System. This practice is intended for dense- and gap- graded mixtures with nominal maximum aggregate sizes to 37.5 mm.
- 1.2 This standard may involve hazardous materials, operations, and equipment, This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to its use.

#### 2. REFERENCED DOCUMENTS

#### 2.1 *AASHTO Standards*

- PP XX-XX, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor
- PP XX-XX, Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Concrete Using the Simple Performance Test System

#### 2.2 *Other Publications*

• Equipment Specification for the Simple Performance Test System, Version 2.0, Prepared for National Cooperative Highway Research Program (NCHRP), March 26, 2004.

#### 3. TERMINOLOGY

3.1 Dynamic Modulus –  $|E^*|$ , the absolute value of the complex modulus calculated by dividing the peak-to-peak stress by the peak-to-peak strain for a material subjected to a sinusoidal loading.

- 3.2 *Phase Angle*  $\delta$ , the angle in degrees between a sinusoidally applied stress and the resulting strain in a controlled-stress test.
- 3.3 *Permanent Deformation* Non-recovered deformation in a repeated load test.
- 3.4 *Confining Pressure* Stress applied to all surfaces in a confined test.
- 3.5 *Deviator Stress* Difference between the total axial stress and the confining pressure in a confined test.
- 3.6 *Flow Number*. The number of load cycles corresponding to the minimum rate of change of permanent axial strain during a repeated load test.

#### 4. SUMMARY OF THE TEST METHODS

- 4.1 This test method describes procedures for measuring the dynamic modulus and flow number for HMA.
- 4.2 In the dynamic modulus procedure an HMA specimen at a specific test temperature is subjected to controlled sinusoidal (haversine) compressive stress of various frequencies. The applied stresses and resulting axial strains are measured as a function of time and used to calculate the dynamic modulus and phase angle.
- 4.3 In the flow number procedure an HMA specimen at a specific test temperature is subjected to a repeated haversine axial compressive load pulse of 0.1 sec every 1.0 sec. The test may be conducted with or without confining pressure. The resulting permanent axial strains are measured as a function of the load cycles and numerically differentiated to calculate the flow number. The flow number is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain.

#### 5. SIGNIFICANCE AND USE

- 5.1 The dynamic modulus is a performance related property that can be used for mixture evaluation and for characterizing the stiffness of HMA for mechanistic-empirical pavement design.
- 5.2 The flow number is a property related to the resistance of HMA mixtures to permanent deformation. It can be used to evaluate mixtures and to design mixtures with specific resistance to permanent deformation.

#### **6.** APPARATUS

- 6.1 Specimen Fabrication Equipment Equipment for fabricating dynamic modulus test specimens as described in AASHTO PP XX-XX, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor.
- 6.2 *Dynamic Modulus Test System* A dynamic test system meeting the requirements of Equipment Specification for the Simple Performance Test System, Version 2.0.
- 6.3 Conditioning Chamber An environmental chamber for conditioning the test specimens to the desired testing temperature. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 4 to 60 °C (39 to 140 °F) to an accuracy of  $\pm$  0.5 °C (1 °F). The chamber shall be large enough to accommodate the number of specimens to be tested plus a dummy specimen with a temperature sensor mounted at the center for temperature verification.
- 6.4 *Teflon Sheet* 0.25 mm (0.001 in) thick to be used as friction reducer between the specimen and the loading platens in the dynamic modulus test.
- 6.5 Latex Membranes 100 mm (4 in) diameter by xxx mm thick for use in confined tests and for manufacturing "double greased latex" friction reducers to be used between the specimen and the loading platens in the flow number test.
- 6.6 Silicone Grease Dow Corning xxx or equivalent for manufacturing "double greased latex" friction reducers to be used between the specimen and the loading platens in the flow number test.
- 6.7 Glass Plates 125 mm (5 in) by 125 mm (5 in) by 6.4 mm (0.25 in) thick to be in manufacturing "double greased latex" friction reducers to be used between the specimen and the loading platens in the flow number test.
- 6.8 Balance Balance with minimum capacity of xx g, capable of weighing to the nearest 0.1 g. The balance is used to weigh silicone grease during fabrication of "double greased latex" friction reducers to be used between the specimen and the loading platens in the flow number test.
- 6.9 Weights xx kg of weights to be in manufacturing "double greased latex" friction reducers to be used between the specimen and the loading platens in the flow number test.

#### 7. HAZARDS

7.1 This practice and associated standards involve handling of hot asphalt binder, aggregates and asphalt mixtures. It also includes the use of sawing and coring

machinery and servo-hydraulic testing equipment. Use standard safety precautions, equipment, and clothing when handling hot materials and operating machinery.

#### 8. STANDARDIZATION

8.1 Items associated with this practice that require calibration are included in the documents referenced in Section 2. Refer to the pertinent section of the referenced documents for information concerning calibration.

#### 9. PROCEDURE A - DYNAMIC MODULUS TEST

- 9.1 *Test Specimen Fabrication*
- 9.1.1 Testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens fabricated in accordance with AASHTO PP XX-XX.
- 9.1.2 Prepare at least two test specimens to the target air void content and aging condition in accordance with AASHTO PP XX-XX.
  - **Note 1 –** A reasonable air void tolerance for test specimen fabrication is  $\pm 0.5$  %.

**Note 2** – The coefficient of variation for properly conducted dynamic modulus tests is approximately 10 %. The coefficient of variation of the mean dynamic modulus for tests on multiple specimens is given by Table 1.

Table 3. Coefficient of Variation for the Mean of Dynamic Modulus Test on Replicate Specimens.

Specimens	Coefficient of Variation
	for the Mean, %
2	7.1
3	5.8
4	5.0
5	4.5
6	4.1
7	3.8
8	3.5
9	3.3
10	3.2

Use Table 1 to select an appropriate number of specimens based on the uncertainty that can be tolerated in the analysis.

- 9.2 Test Specimen Instrumentation (Standard Glued Gage Point System)
- 9.2.1 Attach the gage points to the specimen in accordance with the manufacturers instructions.
- 9.2.2 Confirm that the gage length is 70 mm (2.76 in)  $\pm$  1 mm (0.04 in) measured center to center of the gage points.
- 9.3 *Procedure*
- 9.3.1 Unconfined Tests
- 9.3.1.1 Assemble each specimen to be tested with platens in the following order from bottom to top. Bottom loading platen, bottom Teflon friction reducer, specimen, top Teflon friction, and top loading platen.
- 9.3.1.2 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.
- 9.3.1.3 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.
- 9.3.1.4 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly from the conditioning chamber, and quickly place it in the testing chamber.
- 9.3.1.5 Install the specimen mounted deformation measuring system on the gauge points per the manufacturer's instructions. Ensure that the deformation measuring system is within its calibrated range. Make sure that the top loading platen is free to rotate during loading.
- 9.3.1.6 Close the testing chamber and allow the chamber temperature to return to testing temperature.
- 9.3.1.7 Steps 9.3.1.5 through 9.3.1.7 including return of the test chamber to the target temperature shall be completed in 5 minutes.
- 9.3.1.8 Enter the required identification and control information into the Dynamic Modulus Software.
- 9.3.1.9 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete and display test data and data quality indicators.

- 9.3.1.10 Review the data quality indicators as discussed in Section 9.4 of this test procedure. Retest specimens with data quality indicators above the values specified in Section 9.4.
- 9.3.1.11 Once acceptable data have been collected, open the test chamber, and remove the tested specimen.
- 9.3.1.12 Repeat steps 9.3.1.2 through 9.3.1.11 for the remaining test specimens.

#### 9.3.2 <u>Confined Tests</u>

- 9.3.2.1 Assemble each specimen to be tested with platens and membrane as follows. Place the bottom friction reducer and the specimen on the bottom platen. Stretch the membrane over the specimen and bottom loading platen. Install the lower o-ring seal. Place the top friction reducer and top platen on top of the specimen, and stretch the membrane over the top platen. Install the upper o-ring seal.
- 9.3.2.2 Encase the dummy specimen in a membrane.
- 9.3.2.3 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.
- 9.3.2.4 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.
- 9.3.2.5 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.
- 9.3.2.6 Install the specimen mounted deformation measuring system on the gauge points per the manufacturer's instructions. Ensure that the deformation measuring system is with its calibrated range. Make sure that the top loading platen is free to rotate during loading.
- 9.3.2.7 Close the testing chamber and allow the chamber temperature to return to testing temperature.
- 9.3.2.8 Steps 9.3.2.5 through 9.3.2.7 including return of the test chamber to the target temperature shall be completed in 5 minutes.
- 9.3.2.9 Enter the required identification and control information into the Dynamic Modulus Software.

- 9.3.2.10 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete and display test data and data quality indicators.
- 9.3.2.11 Review the data quality indicators as discussed in Section 9.4 of this test procedure. Retest specimens with data quality indicators above the values specified in Section 9.4.
- 9.3.2.12 Once acceptable data have been collected, open the test chamber, and remove the tested specimen.
- 9.3.2.13 Repeat steps 9.3.2.3 through 9.3.2.12 for the remaining test specimens.
- 9.4 *Computations and Data Quality*
- 9.4.1 The calculation of dynamic modulus, phase angle, and the data quality indicators is performed automatically by the Simple Performance Test System software.
- 9.4.2 Accept only test data meeting the data quality statistics given in Table 2. Repeat tests as necessary to obtain test data meeting the data quality statistics requirements.

**Table 4. Data Quality Statistics Requirements.** 

<b>Data Quality Statistic</b>	Limit
Peak to Peak Strain	85 to 115 µstrain
Load standard error	10 %
Deformation standard error	10 %
Deformation uniformity	20 %
Phase uniformity	3 degrees

- **Note 3** The data quality statistics in Table 2 are reported by the Simple Performance Test System software. If a dynamic modulus test system other than the Simple Performance Test System is used, refer to Equipment Specification for the Simple Performance Test System, Version 2.0 for algorithms for computation of dynamic modulus, phase angle, and data quality statistics.
- 9.5 *Reporting*
- 9.5.1 Test temperature.
- 9.5.2 Confining stress level.
- 9.5.3 Average and standard deviation of dynamic modulus and phase angle for the replicated specimens tested.

9.5.4 Attach Simple Performance Test System standard dynamic modulus summary report.

#### **10.** PROCEDURE B – FLOW NUMBER TEST

- 10.1 *Test Specimen Fabrication*
- Testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens fabricated in accordance with AASHTO PP XX-XX.
- Prepare at least three test specimens to the target air void content and aging condition in accordance with AASHTO PP XX-XX.
  - **Note 4 –** A reasonable air void tolerance for test specimen fabrication is  $\pm 0.5$  %.
  - **Note 5** The coefficient of variation for the permanent deformation before flow in the flow number test is approximately 15 %. The coefficient of variation for the flow number is approximately 20 %. The coefficient of variation of the mean for tests on multiple specimens is given by Table 3.

Table 5. Coefficient of Variation for the Mean of Properties From the Flow Number Test

	Coefficient of Variation for the Mean, %						
Specimens	Permanent Deformation	Flow Number					
	Before Flow						
2	5.6	8.4					
3	6.2	8.0					
4	6.7	7.7					
5	7.1	7.5					
6	7.4	7.3					
7	7.7	7.2					
8	8.0	7.1					
9	8.2	7.0					
10	8.4	6.9					

Use Table 3 to select an appropriate number of specimens based on the uncertainty that can be tolerated in the analysis.

#### 10.2 Unconfined Tests

10.2.1 Prepare two "greased double latex" end friction reducers for each specimen that will be tested using the procedure specified in Appendix A. It is recommended that new friction reducers be used for each test.

- Assemble each specimen to be tested with platens in the following order from bottom to top. Bottom loading platen, bottom "double greased latex" friction reducer, specimen, top "double greased latex" friction reducer, and top loading platen.
- 10.2.3 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.
- 10.2.4 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.
- 10.2.5 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.
- 10.2.6 Close the testing chamber and allow the chamber temperature to return to testing temperature. Make sure that the top loading platen is not permitted to rotate during loading.
- 10.2.7 Steps 10.2.5 and 10.2.6 including return of the test chamber to the target temperature shall be completed in 5 minutes.
- 10.2.8 Enter the required identification and control information into the Flow Number Software.
- Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete.
- 10.2.10 Upon completion of the test, open the test chamber, and remove the tested specimen.
- 10.2.11 Repeat steps 10.2.5 through 10.2.10 for the remaining test specimens.

#### 10.3 <u>Confined Tests</u>

- 10.3.1 Prepare two "greased double latex" end friction reducers for each specimen that will be tested using the procedure specified in Appendix A. It is recommended that new friction reducers be used for each test.
- Assemble each specimen to be tested with platens and membrane as follows. Place the bottom "double greased latex" friction reducer and the specimen on the bottom platen. Stretch the membrane over the specimen and bottom loading platen. Install the lower o-ring seal. Place the top "double greased latex" friction reducer and top platen on top of the specimen, and stretch the membrane over the top platen. Install the upper o-ring seal.

- 10.3.3 Encase the dummy specimen in a membrane.
- 10.3.4 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.
- 10.3.5 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.
- 10.3.6 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.
- 10.3.7 Close the testing chamber and allow the chamber temperature to return to testing temperature. Make sure that the top loading platen is not permitted to rotate during loading.
- 10.3.8 Steps 10.3.6 and 10.3.7 including return of the test chamber to the target temperature shall be completed in 5 minutes.
- 10.3.9 Enter the required identification and control information into the Flow Time Software.
- 10.3.10 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete.
- 10.3.11 Upon completion of the test, open the test chamber, and remove the tested specimen.
- 10.3.12 Repeat steps 10.3.6 through 10.3.11 for the remaining test specimens.
- 10.4 *Calculations*
- 10.4.1 The calculation of the permanent deformation for each load cycle and the flow number for individual specimens is performed automatically by the Simple Performance Test System software.
- 10.4.2 Compute the average and standard deviation of the flow numbers for the replicate specimens tested.
- 10.4.3 Compute the average and standard deviation of the permanent deformation at the load cycles of interest.
- 10.4.4 Attach Simple Performance Test System flow number test summary report.

#### 11. KEYWORDS

Dynamic modulus, phase angle, flow number, permanent deformation, repeated load testing.

### APPENDIX A. METHOD FOR PREPARING GREASED DOUBLE LATEX END FRICTION REDUCERS FOR THE FLOW NUMBER TEST (MANDATORY INFORMATION)

#### **A2.** PURPOSE

- A3.13 This Appendix presents a procedure for fabricated "greased double latex' end friction reducers for the flow number test.
- A3.14 These end friction reducers are mandatory for the flow number test.

#### A4. SUMMARY

"Greased double latex" end friction reducers are fabricated by cutting two circular latex sheets from a latex membrane used for used confining specimens, applying a specified weight of silicone grease, then compressing the two circular latex sheets between glass plates using a specified weight.

#### A5. PROCEDURE

- A5.1 Cut a xx mm (yy in) thick latex membrane along its long axis to obtain a rectangular sheet of latex. The sheet will be approximately 315 mm (12.5 in) by 250 mm (10 in).
- A5.2 Trace the circumference of the loading platen on the sheet of latex, the cut along the tracing to form circular latex sheets that are slightly larder than the loading platen. Four are needed to fabricate friction reducers for the top and bottom of the specimen.
- A5.3 Place one circular latex sheet on the balance and weigh xx g of silicone grease onto the latex sheet.
- A5.4 Place a second circular latex sheet on top of the silicone grease.
- A5.5 Place the two latex sheets with the silicone grease between them on a glass plate.
- A5.6 Place a second glass plate on top of the two latex sheets.

- A5.7 Place a xx kg mass on the top glass plate. Some silicone grease will be squeezed out under the weight.
- A5.8 After the silicone grease compresses, remove the weight and top glass plate from the "greased double latex" friction reducer. Wipe the excess silicone grease from the friction reducer and the glass plates.
- A5.9 If the friction reducer will be used in confined tests, cut punch a hole through both latex sheets at the location of the vent in the loading platen.

#### **Proposed Standard Practice for**

# Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Concrete Using the Simple Performance Test System

**AASHTO Designation: PP XX-XX** 

#### 1. SCOPE

- 1.1 This practice describes testing and analysis for developing a dynamic modulus master curve for hot-mix asphalt concrete using the Simple Performance Test System. This practice is intended for dense- and gap- graded mixtures with nominal maximum aggregate sizes to 37.5 mm.
- 1.2 This standard may involve hazardous materials, operations, and equipment, This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to its use.

#### 2. REFERENCED DOCUMENTS

#### 2.1 *AASHTO Standards*

• PP XX-XX, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor

#### 2.2 *Other Publications*

• Equipment Specification for the Simple Performance Test System, Version 2.0, Prepared for National Cooperative Highway Research Program (NCHRP), March 26, 2004.

#### 3. TERMINOLOGY

- 3.1 *Dynamic Modulus Master Curve* a composite curve constructed at a reference temperature by shifting dynamic modulus data from various temperatures along the log frequency axis.
- 3.2 *Reduced Frequency* The computed frequency at the reference temperature equivalent to the actual loading frequency at the test temperature.

- 3.3 *Reference Temperature* The temperature at which the master curve is constructed.
- 3.4 *Shift Factor* shift in frequency associated with a shift from a test temperature to the reference temperature.

#### 4. SUMMARY OF PRACTICE

4.1 This practice describes the testing and analysis needed to develop a dynamic modulus master curve for hot-mix asphalt concrete mixtures. It involves collecting dynamic modulus test data at specified temperatures and loading rates, then manipulating the test data to obtain a continuous function describing the dynamic modulus as a function of frequency and temperature.

#### 5. SIGNIFICANCE AND USE

5.1 Dynamic modulus master curves can be used for mixture evaluation and for characterizing the modulus of hot-mix asphalt concrete for mechanistic-empirical pavement design.

#### 6. APPARATUS

- 6.1 *Specimen Fabrication Equipment* Equipment for fabricating dynamic modulus test specimens as described in AASHTO PP XX-XX, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor.
- 6.2 *Dynamic Modulus Test System* A dynamic test system meeting the requirements of Equipment Specification for the Simple Performance Test System, Version 2.0.
- 6.3 *Analysis Software* Software capable of performing numerical optimization of nonlinear equations.
  - **Note 1 -** The Solver Tool included in Microsoft Excel® is capable of performing the numerical optimization required by this practice.

#### 7. HAZARDS

7.1 This practice and associated standards involve handling of hot asphalt binder, aggregates and asphalt mixtures. It also includes the use of sawing and coring machinery and servo-hydraulic testing equipment. Use standard safety precautions, equipment, and clothing when handling hot materials and operating machinery.

#### 8. STANDARDIZATION

8.1 Items associated with this practice that require calibration are included in the documents referenced in Section 2. Refer to the pertinent section of the referenced documents for information concerning calibration.

#### 9. DYNAMIC MODULUS TEST DATA

- 9.1 *Test Specimen Fabrication*
- 9.1.1 Prepare at least two test specimens to the target air void content and aging condition in accordance with AASHTO PP XX-XX.
  - **Note 2 –** A reasonable air void tolerance for test specimen fabrication is  $\pm 0.5$  %.
  - **Note 3** The coefficient of variation for properly conducted dynamic modulus tests is approximately 13 %. The coefficient of variation of the mean dynamic modulus for tests on multiple specimens is given by Table 1.

Table 6. Coefficient of Variation for the Mean of Dynamic Modulus Test on Replicate Specimens.

Specimens	Coefficient of Variation							
	For the Mean							
2	9.2							
3	7.5							
4	6.5							
5	5.8							
6	5.3							
7	4.9							
8	4.6							
9	4.3							
10	4.1							

Use Table 1 to select an appropriate number of specimens based on the uncertainty that can be tolerated in the analysis.

- 9.1.2 Record the following volumetric properties for each test specimen:
  - Voids in the mineral aggregate (VMA)
  - Voids filled with asphalt concrete (VFA)

#### 9.2 *Testing Conditions*

9.2.1 Measure the dynamic modulus and phase angle of each specimen using the dynamic modulus test system at each of the temperatures and loading frequencies given in Table 2. Begin testing at the lowest temperature and highest frequency. Test all frequencies in descending order before moving to the next highest temperature.

**Table 7. Recommended Testing Temperatures and Loading Frequencies.** 

PG 58-XX	and softer	PG 64-XX &	& PG 70-XX	PG 76 –XX and stiffer		
Temperature	Loading	Temperature	Loading	Temperature	Loading	
°C	Frequencies	°C	Frequencies	°C	Frequencies	
	Hz		Hz		Hz	
4	10, 1, 0.1	4	10, 1, 0.1	4	10, 1, 0.1	
20	10, 1, 0.1	20	10, 1, 0.1	20	10, 1, 0.1	
35	10, 1, 0.1,	40	10, 1, 0.1,	45	10, 1, 0.1,	
	and 0.01		and 0.01		and 0.01	

**Note 4 –** The dynamic modulus testing may be performed with or without confinement. The same confining stress conditions must be used at all temperatures and loading rates. An unconfined dynamic modulus master curve is typically used in mechanistic-empirical pavement analysis methods.

9.2.2 Accept only test data meeting the data quality statistics given in Table 3. Repeat tests as necessary to obtain test data meeting the data quality statistics requirements.

**Table 8. Data Quality Statistics Requirements.** 

<b>Data Quality Statistic</b>	Limit
Load standard error	10 %
Deformation standard error	10 %
Deformation uniformity	20 %
Phase uniformity	3 degrees

**Note 5** – The data quality statistics in Table 3 are reported by the Simple Performance Test System software. If a dynamic modulus test system other than the Simple Performance Test System is used, refer to Equipment Specification for the Simple Performance Test System, Version 2.0 for algorithms for computation of dynamic modulus, phase angle, and data quality statistics.

- 9.3 Dynamic Modulus Data Summary
- 9.3.1 Prepare a summary table of the dynamic modulus data. At each temperature and frequency, compute:
  - 1. Average dynamic modulus
  - 2. Average phase angle

- 3. Dynamic modulus coefficient of variation
- 4. Standard deviation of phase angle

Figure 1 presents an example summary data sheet.

Conditions		Specimer	า 1	Specimer	n 2	Specimer	า 3	Average	Modulus	Average	Std Dev
Temperature	Frequency	Modulus	Phase Angle	Modulus	Phase Angle	Modulus	Phase Angle	Modulus	CV	Phase	Phase
С	Hz	Ksi	Degree	Ksi	Degree	Ksi	Degree	Ksi	%	Deg	Deg
4	0.1	1170.9	18.8	1214.8	19.6	1443.2	18.5	1276.3	11.5	19.0	0.5
4	1	1660.8	12.0	1743.5	12.5	2027.0	11.6	1810.5	10.6	12.0	0.4
4	10	2107.3	8.1	2245.6	8.4	2596.1	8.2	2316.3	10.9	8.2	0.2
20	0.1	259.1	33.9	289.9	33.5	315.2	34.6	288.1	9.8	34.0	0.6
20	1	604.1	27.4	657.3	26.8	711.2	27.0	657.5	8.1	27.1	0.3
20	10	1065.1	21.0	1181.5	18.8	1231.4	19.8	1159.3	7.4	19.9	1.1
40	0.01	17.2	18.6	16.5	18.8	18.8	19.2	17.5	6.7	18.9	0.3
40	0.1	26.5	24.8	26.4	26.1	30.6	26.0	27.8	8.6	25.6	0.7
40	1	62.9	31.5	63.9	32.1	74.5	32.7	67.1	9.6	32.1	0.6
40	10	180.1	35.2	197.6	35.1	220.6	35.2	199.4	10.2	35.2	0.1

Figure 1. Example Dynamic Modulus Summary Sheet.

#### **10.** DATA ANALYSIS

- 10.1 Dynamic Modulus Master Curve Equation
- 10.1.1 <u>General Form.</u> The general form of the dynamic modulus master curve is a modified version of the dynamic modulus master curve equation included in the Mechanistic Empirical Design Guide (MEDG) (Applied Research Associates, Inc., 2004)

$$\log |E^*| = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma \log \omega_r}} \tag{1}$$

where:

| E\* | = dynamic modulus, psi

 $\omega_r$  = reduced frequency, Hz

Max = limiting maximum modulus, psi

 $\delta$ ,  $\beta$ , and  $\gamma$  = fitting parameters

10.1.2 <u>Reduced Frequency.</u> The reduce frequency in Equation 1 is computed using the Arrhenius equation.

$$\log \omega_r = \log \omega + \frac{\Delta E_a}{19.14714} \left( \frac{1}{T} - \frac{1}{T_r} \right) \tag{2}$$

where:

 $\omega_{\text{r}} = \text{reduced}$  frequency at the reference temperature

 $\omega$  = loading frequency at the test temperature

 $T_r$  = reference temperature,  ${}^{\circ}K$ 

T = test temperature, °K

 $\Delta E_a$  = activation energy (treated as a fitting parameter)

10.1.3 <u>Final Form.</u> The final form of the dynamic modulus master curve equation is obtained by substituting Equation 2 into Equation 1.

$$\log |E^*| = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma \left\{ \log \omega + \frac{\Delta E_a}{19.14714} \left[ \left( \frac{1}{T} \right) - \left( \frac{1}{T_r} \right) \right] \right\}}}$$
(3)

10.2 *Shift Factors.* The shift factors at each temperature are given by Equation 4,

$$\log[a(T)] = \frac{\Delta E_a}{19.14714} \left(\frac{1}{T} - \frac{1}{T_r}\right) \tag{4}$$

where:

a(T) = shift factor at temperature T

 $T_r$  = reference temperature, °K

T = test temperature, °K

 $\Delta E_a$  = activation energy (treated as a fitting parameter)

10.3 *Limiting Maximum Modulus*. The maximum limiting modulus is estimated from mixture volumetric properties using the Hirsch model (Christensen, et. al, 2005) and a limiting binder modulus of 1 GPa (145,000 psi), Equations 5 and 6.

$$|E^*|_{\text{max}} = P_c \left[ 4,200,000 \left( 1 - \frac{VMA}{100} \right) + 435,000 \left( \frac{VFA \times VMA}{10,000} \right) \right] + \frac{1 - P_c}{\left[ \left( 1 - \frac{VMA}{100} \right) + \frac{VMA}{435,000(VFA)} \right]}$$
(5)

where

$$P_{c} = \frac{\left(20 + \frac{435,000(VFA)}{VMA}\right)^{0.58}}{650 + \left(\frac{435,000(VFA)}{VMA}\right)^{0.58}}$$
(6)

 $|E^*|_{max}$  = limiting maximum mixture dynamic modulus, psi

VMA = Voids in mineral aggregates, %

VFA = Voids filled with asphalt, %

- 10.4 Fitting the Dynamic Modulus Master Curve
- 10.4.1 Step 1. Estimate Limiting Maximum Modulus

- 10.4.1.1 Using the average VMA and VFA of the specimens tested, compute the limiting maximum modulus using Equations 5 and 6.
- 10.4.1.2 Compute the logarithm of the limiting maximum modulus and designate this as *Max*
- 10.4.2 <u>Step 2. Select a the Reference Temperature</u>
- 10.4.2.1 Select the reference temperature for the dynamic modulus master curve and designate this as  $T_r$ . Usually 20 °C (293.15 °K) is used as the reference temperature.
- 10.4.3 Step 3. Perform Numerical Optimization
- 10.4.3.1 Substitute Max computed in Section 10.4.1.2 and  $T_r$  selected in Section 10.4.2.1 into Equation 3.
- 10.4.3.2 Determine the four fitting parameters of Equation 3 ( $\delta$ ,  $\beta$ ,  $\gamma$ , and  $\Delta E_a$ ) using numerical optimization. The optimization can be performed using the Solver function in Mircosoft EXCEL®. This is done by setting up a spreadsheet to compute the sum of the squared errors between the logarithm of the average measured dynamic moduli at each temperature/frequency combination and the values predicted by Equation 3. The Solver function is used to minimize the sum of the squared errors by varying the fitting parameters in Equation 3. The following initial estimates are recommended:  $\delta$  = 0.5,  $\beta$  = -1.0,  $\gamma$ =-0.5, and  $\Delta E_a$  = 200,000.
- 10.4.4 Step 4. Compute Goodness of Fit Statistics
- 10.4.4.1 Compute the standard deviation of the logarithm of the average dynamic modulus values for each temperature/frequency combination. Designate this vale as  $S_v$ .
- 10.4.4.2 Compute the standard error of estimate using Equation 7.

$$S_{e} = \left[\frac{1}{6} \sum_{i=1}^{10} \left( \log \left| \hat{E} * \right|_{i} - \log \left| E * \right|_{i} \right)^{2} \right]^{0.5}$$
 (7)

where:

 $S_e$  = standard error of estimate

 $\log |\hat{E}^*|_{\rm i} = {\rm value~predicted~by~Equation~3~after~optimization~for~each}$  temperature/frequency combination

 $\log |E^*|_i = \text{logarithm of the average measured dynamic modulus for each temperature/frequency combination.}$ 

10.4.4.3 Compute the explained variance, R<sup>2</sup>, using Equation 8.

$$R^2 = 1 - \frac{8S_e^2}{9S_v^2} \tag{8}$$

where:

 $R^2$  = explained variance

 $S_e$  = standard error of estimate from Equation 7.

 $S_y = standard$  deviation of the of the logarithm of the average dynamic modulus values for each temperature/frequency combination

- 10.5 Evaluate Fitted Master Curve
- 10.5.1 The ratio of  $S_e$  to  $S_v$  should be less than 0.05
- 10.5.2 The explained variance should exceed 0.99

#### 11. REPORT

- 11.1 Mixture identification
- Measured dynamic modulus and phase angle data for each specimen at each temperature/frequency combination
- 11.3 Average dynamic modulus and phase angle at each temperature/frequency combination
- 11.4 Coefficient of variation of the measured dynamic modulus data at each temperature/frequency combination
- 11.5 Standard deviation of the phase angle data at each temperature/frequency combination.
- 11.6 VMA and VFA of each specimen tested
- 11.7 Average VMA and VFA for the specimens tested
- 11.8 Reference temperature
- 11.9 Parameters of the fitted master curve (Max,  $\delta$ ,  $\beta$ ,  $\gamma$ , and  $\Delta E_a$ )
- 11.10 Goodness of fit statistics for the fitted master curve (S<sub>e</sub>, S<sub>y</sub>, S<sub>e</sub>/S<sub>y</sub>, R<sup>2</sup>)
- 11.11 Plot of the fitted dynamic modulus master curve as a function of reduced frequency showing average measured dynamic modulus data
- 11.12 Plot of shift factors as a function of temperature

11.13 Plot of average phase angle as a function of reduced frequency.

#### 12. KEYWORDS

12.1 Dynamic modulus, phase angle, master curve

#### **13.** REFERENCES

- 13.1 Applied Research Associates, Inc., ERES Consultants Division *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*, Final Report Prepared for the National Cooperative Highway Research Program, March, 2004.
- 13.2 Christensen, D.W., Pellinen, T.K., Bonaquist, R.F., "Hirsch Model for Estimating the Modulus of Asphalt Concrete," *Journal of the Association of Asphalt Paving Technologists*, Vol 72, 2003.